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AD-A234 744

GL-TR-90-0145

Development of a Vector Spherical Harmonic (VSH) Model of the Neutral Thermosphere

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Space Physics Research Laboratory
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Ann Arbor, Michigan 48109

March 1990.

Scientific Report No. 1

Approved for public release; distribution unlimited

GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

"This technical report has been reviewed and is approved for publication"

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For the Commander

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704 0188

[illegible]

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1990	Scientific Report No. 1

4. TITLE AND SUBTITLE

Development of a Vector Spheric Harmonic (VSH) Model of the Neutral Thermosphere

5. FUNDING NUMBERS

PE 63707F
PR 2688 TA 04 WU JA
Contract F19628-89-K-0026

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Geophysics Laboratory
Hanscom AFB
Bedford, MA 01731-5000

Contract Manager: Frank Marcos/LIS

10. SPONSORING MONITORING AGENCY REPORT NUMBER

GL-TR-90-0145

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Air Force has requirements for accurate knowledge and specification of the state variables of the Earth's thermosphere. Work done under this contract will lead to a new model of global thermospheric density that can be used to specify and forecast neutral densities, temperatures, and winds for a wide range of solar and geomagnetic activity. The model will be based on simulations made with the National Center for Atmospheric Research (NCAR) Thermosphere/Ionosphere General Circulation Model (TIGCM) and on data. It will be capable of using real-time geophysical indices or data from ground-based and satellite inputs and will provide neutral variables at specified locations and times in the altitude range 90 - 1500 km. This hybrid theoretical and semi-empirical model will be based on a new Vector Spherical Harmonic (VSH) analysis technique developed at the University of Michigan that permits the incorporation of the TIGCM outputs and data into the model. The VSH model will be provided for use by the Air Force in an operational setting and will be a more accurate version of existing models of the neutral upper atmosphere.

This technical report describes the progress of the University of Michigan and National Center for Atmospheric Research teams in the development of the hybrid model. Scientific progress and plans are reported for each quarterly reporting interval throughout the first year of the project.

14. SUBJECT TERMS

Thermospheric Composition
Thermospheric Dynamics
Vector Spheric Harmonic

15. NUMBER OF PAGES

162

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

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Executive Summary

The Air Force has requirements for accurate knowledge and specification of the state variables of the Earth's thermosphere. Work done under this contract will lead to a new model of global thermospheric density that can be used to specify and forecast neutral densities, temperatures, and winds for a wide range of solar and geomagnetic activity. The model will be based on simulations made with the National Center for Atmospheric Research (NCAR) Thermosphere/Ionosphere General Circulation Model (TIGCM) and on data. It will be capable of using real-time geophysical indices or data from ground-based and satellite inputs and will provide neutral variables at specified locations and times in the altitude range 90 - 1500 km. This hybrid theoretical and semi-empirical model will be based on a new Vector Spherical Harmonic (VSH) analysis technique developed at the University of Michigan that permits the incorporation of the TIGCM outputs and data into the model. The VSH model will be provided for use by the Air Force in an operational setting and will be a more accurate version of existing models of the neutral upper atmosphere.

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1.0 Quarterly Status Report #1 - 1 April 1989 through 30 June 1989

THE UNIVERSITY OF MICHIGAN

SPACE PHYSICS RESEARCH LABORATORY

Quarterly Status Report #1
Covering the Period 1 April 1989 through 30 June 1989
University of Michigan Account 080063

DEVELOPMENT OF A VECTOR SPHERICAL HARMONIC (VSH) MODEL OF THE NEUTRAL THERMOSPHERE

by

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AFGL Contract F19628-89-K-0026

Prepared for:

Air Force Geophysics Laboratory
Air Force Systems Command
L.G. Hanscom Air Force Base
Bedford, Massachusetts 01731

ATTN: Dr. Frank Marcos

1.1 Summary of Objectives of Contract.

The Air Force has requirements for accurate knowledge and specification of the state variables of the Earth's thermosphere. Work done under this contract will lead to a new model of global thermospheric density that can be used to specify and forecast neutral densities, temperatures, and winds for a wide range of solar and geomagnetic activity. The model will be based on simulations made with the National Center for Atmospheric Research (NCAR) Thermospheric/Ionospheric General Circulation Model (TIGCM) and on data. The model will be capable of using real-time geophysical indices or data from ground-based and satellite inputs and will provide neutral variables at specified locations and times in the altitude range 90 - 1500 km. The model will be semi-empirical and will be based on a new vector spherical harmonic (VSH) analysis technique developed at the University of Michigan that permits the incorporation of the TIGCM outputs into the model. The model will be provided for use by the Air Force in an operational setting as a more accurate version of existing models of the neutral upper atmosphere.

1.2 Plans for the next reporting period.;

Plans for the next quarter of effort relate to the work statement given in the original proposal. The timeline for model development is given in Appendix 1.1. Work to verify the TIGCM in the altitude region above 250 km is underway. Two major case studies are planned, one involving 10 days of data from the Dynamics Explorer satellite in 1983 and one involving a previous isolated geomagnetic storm study. The Dynamics Explorer data has been provided to Dr. Roble and a series of TIGCM runs are planned that will be extensively analyzed as part of the verification effort. Dr. Roble has prepared a computer animation of the isolated storm study that will be shown at the CEDAR meeting in June 1989. Considerable effort at the University of Michigan will be made to speed up the current VSH algorithm. It is anticipated that an increase in speed of about a factor of 6-10 can be realized. Further work will be carried out to define the VSH library approach. Work will be also carried out to define the TIGCM input stategy for this program, as well as to incorporate data from Dynamics Explorer into the VSH model for a few cases using an objective analysis scheme.

NTM model timeline

Task	Subtask	Resp Org	FY89 DJFMAMJJAS	FY90 OND JFMAMJJAS	FY91 ONDJFMAMJJAS	FY92 ONDJFMAMJJAS	FY93 ONDJFMAMJJAS	FY94 OND
1	Program definition	Mich/NCAR	•					
2	TIGCM Verification		•					
3	TIGCM frozen	NCAR	•					
4	VSH technique defn.	Mich	•					
	Library approach	Mich	•					
	TIGCM input strat.	NCAR/Mich	•					
5	Sensitivity	NCAR/Mich		•				
	Defn. of # of runs	NCAR/Mich		•				
6	TIGCM runs Phase I	NCAR		•				
7	Merger TIGCM/exp.	Mich		•				
	DE data, SETA data	Mich		•				
	Delivery NTM mk1	Mich/NCAR		•				
8	TIGCM runs Phase II	NCAR/Mich			•			
	Verification >140 km	NCAR/Mich			•			
9	NTM mk 2	Mich/NCAR			•			
	Verification of NTM	Mich/Ncar			•			
10	NTM mk 3	Mich/NCAR				•		
	Verification of NTM							
11	Feasibility of operational TIGCM	Mich/NCAR				•		
12	Deliver operational TIGCM	Mich/NCAR					•	
13	Final validation and final model improvements	Mich/NCAR						•
	Quarterlies		• • •	• • • •	• • • •	• • •	• • • •	•

Appendix I.1

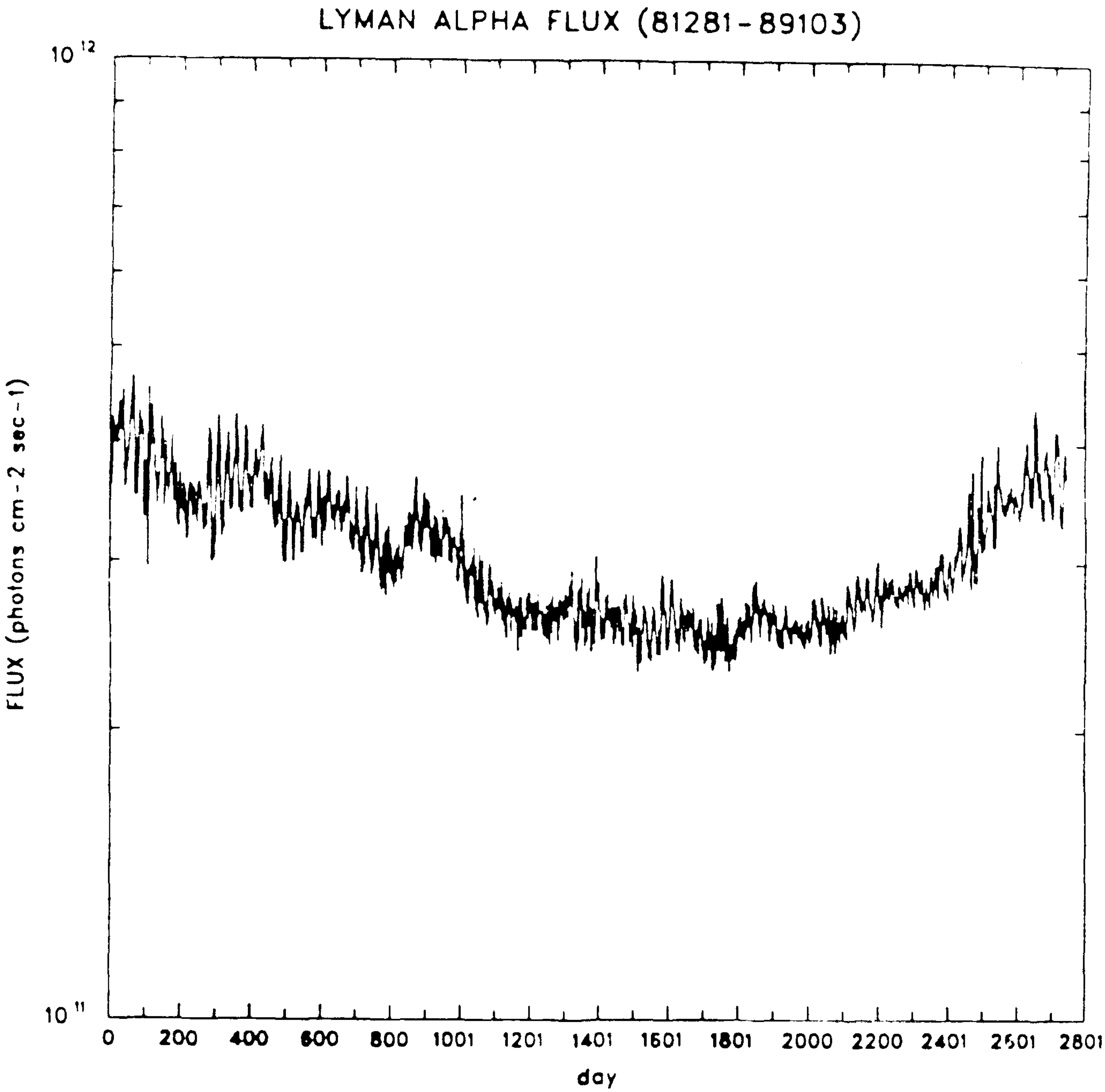

LYMAN ALPHA FLUX (81281-89103)
10^{12}
10^{11}
FLUX (photons cm-2 sec-1)
0
200
400
600
800
1001
1201
1401
1601
1801
2000
2200
2401
2601
2801
day

Fig. 1

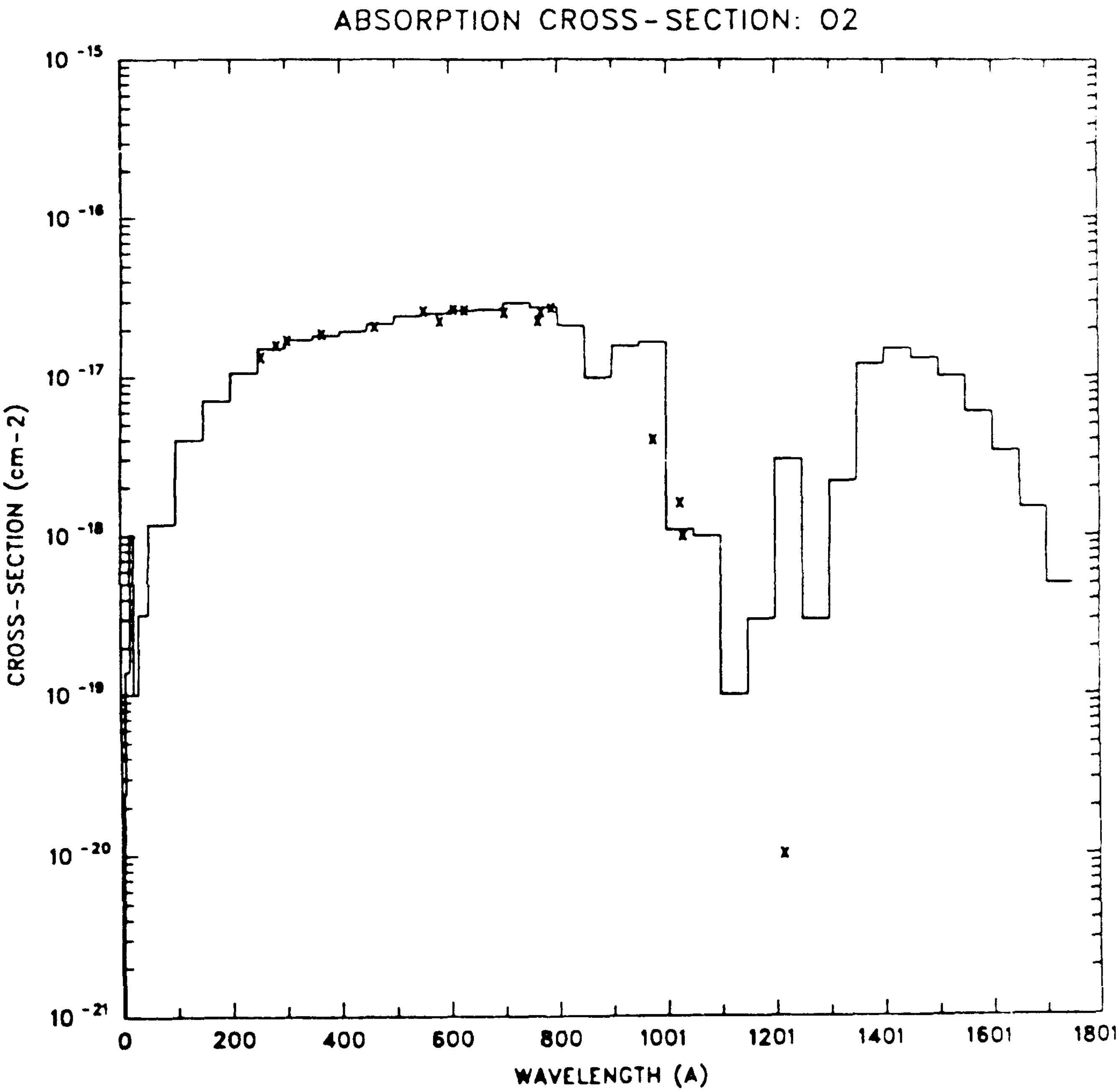
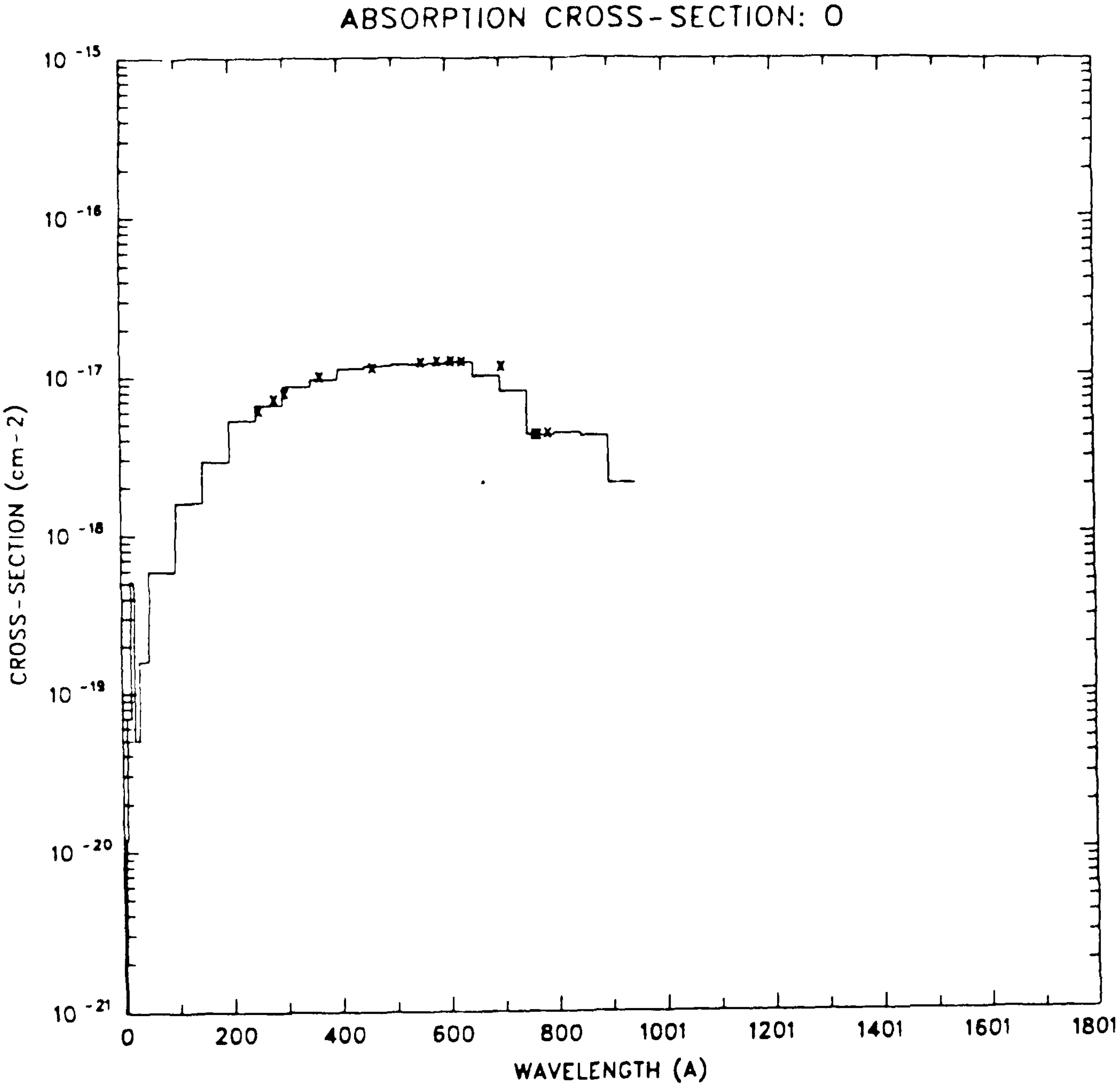
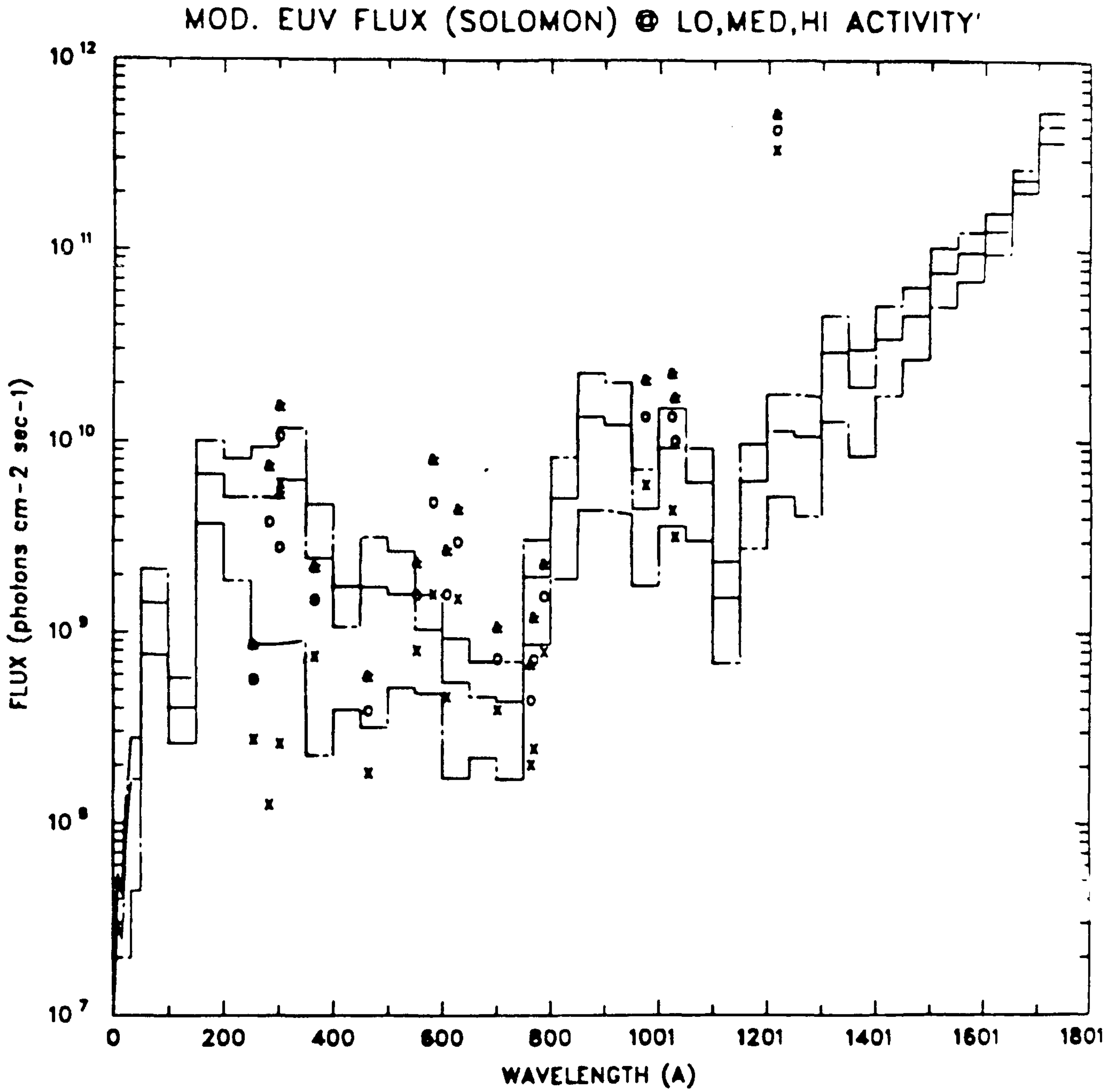

ABSORPTION CROSS-SECTION: O2
CROSS-SECTION (cm-2)
WAVELENGTH (A)
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
0
200
400
600
800
1001
1201
1401
1601
1801

Fig. 2



ABSORPTION CROSS-SECTION: O
10 -15
10 -16
10 -17
10 -18
10 -19
10 -20
10 -21
CROSS-SECTION (cm-2)
0
200
400
600
800
1001
1201
1401
1601
1801
WAVELENGTH (A)

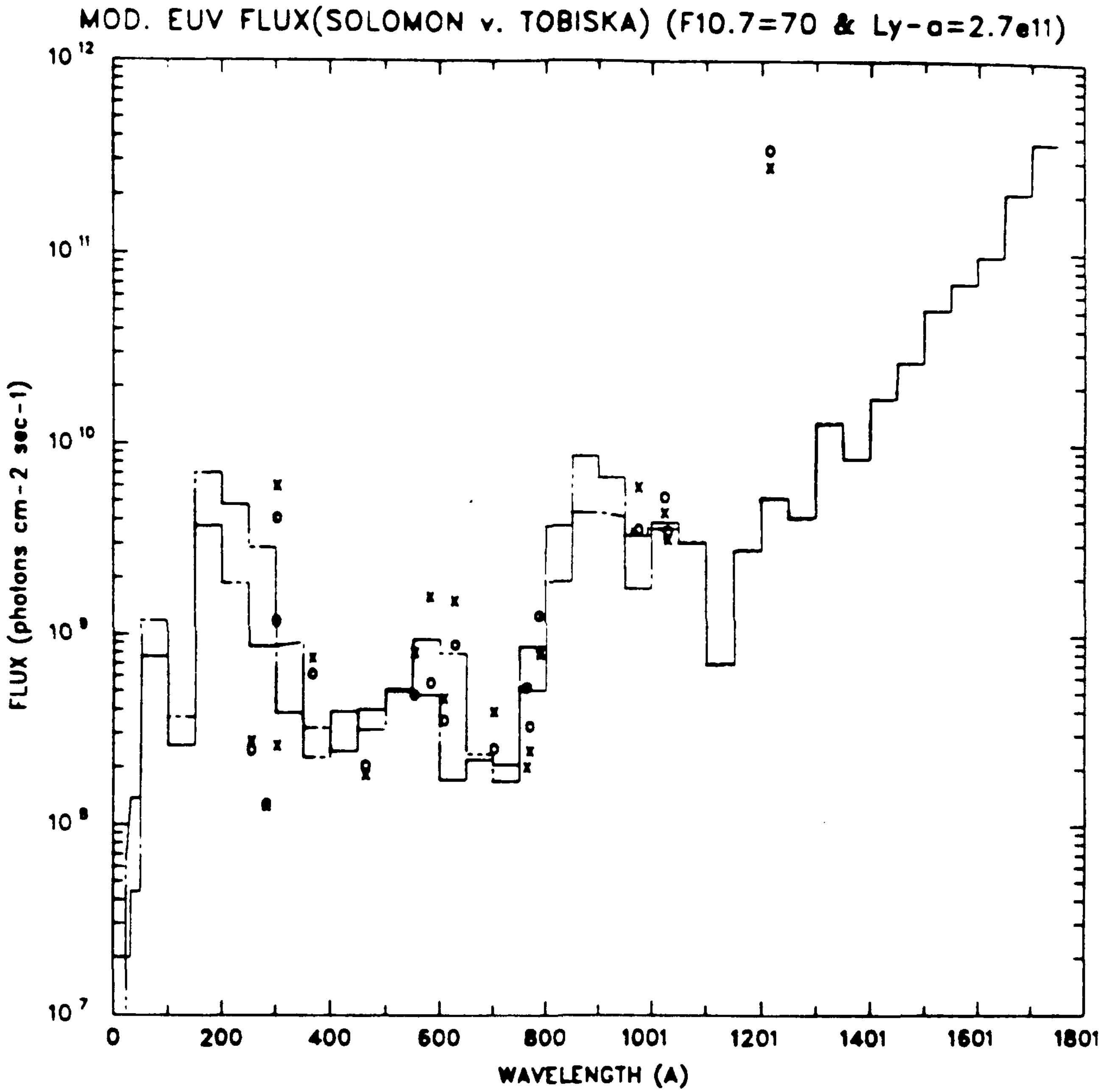
Fig. 3



LO - F10.7 = 70; Ly - α = 27ell ________ _ ____________ X
MED - F10.7 = 220; Ly -α = 82ell ________ _ _ ___________ O
HI - F10.7 = 370; Ly -α = 5.6ell ________ _ _ _ __________ &

X, O, & - discrete lines
square curve - continuous λ intervals

Fig. 4



Solomon ____________ _ ____________ X

Tobiska ____________ _ _ ____________ O

Fig. 5

2.0 Quarterly Status Report #2: 1 July 1989 - 31 October 1989

THE UNIVERSITY OF MICHIGAN

SPACE PHYSICS RESEARCH LABORATORY

Quarterly Status Report #2
Covering the Period 1 July 1989 through 31 October 1989
University of Michigan Account 080063

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During the past reporting period, the effort at the University of Michgian has focussed on the development and improvement of the basic algorithm, based on the vector spherical harmonic expansion of TIGCM calculations. The speed of the routine has been increased by a factor of 6 by developing more efficient loops, etc. In addition, documantation has been produced to facilitate testing of the routine by AFGL. A preliminary version of the VSH model was sent to AFGL for evaluation, complete with 12 sets of coefficients, documentation and source code. In addition, a perliminary version of the planned objective analysis scheme for the ingestion of experimental data was developed, using thermospheric wind measurements from Dynamics Explorer as a first test case. This work led successfully to the development of a semi-empirical model of polar thermosphere dynamics.

Work at the National Center for Atmospheric Research has continued to focus on improvements to the TIGCM and on validation studies involving data/theory comparisons. A specific comparison between TIGCM calculations and SETA data has produced encouraging results indicating that the TIGCM can predict density perturbations with reasonable accuracies (see below for details).

Scientists from the Unviersity of Michigan and from NCAR attended the second quarterly review meeting in Boulder on 21 September 1989. This meeting was also attended by many other scientists from various institutions as well as Air Force Personnel.

Plans for the next reporting period include the further development of the VSH approach, leading to delivery of the Phase 1 Model at the end of FY 1990. Additional key validation and model improvement efforts will be carried out at NCAR.

2.1 Progress during the current reporting period.

Progress during the current reporting period was presented at the second quarterly meeting in Boulder, Colorado on September 21 1989. The detailed agenda for this meeting is shown in Appendix 2.1. Presentations were made by Prof Killeen of the Unviersity of Michigan and Dr. Roble of NCAR and materials from their presentations are included as appendicies to this report.

Prof. Killeen presented the work carried out in association with the VSH development effort. Appendix 2.2 presents current documentation for the model, including a "top down" structural design description, a list of available coefficient sets, a model variable directory, and a description of the input and output variables.

Prof. Killeen also discussed the schedule for the effort (see Appendix 2.3). The overall model development effort is broken down into 13 sub-tasks. Tasks 1-5 have been initiated and task 1 completed. Although the program had a late start in March 1989, the work is on schedule for delivery of the Pase I model at the end of FY 1990.

The University of Michigan subcontract to NCAR has been established and a division of responsibilities for the team at the two institutions has been agreed upon. An initial bench-test version of the VSH model has been delivered to AFGL for evaluation. It is anticipated that early iterations of this type will ensure an improved Phase 1 Model.

An objective analysis scheme was developed for the incorporation of neutral wind measurements from Dynamics Explorer into the VSH model. Averaged wind measurements for the high latitude regions of both hemispheres were binned according to IMF By and Kp indices. The averaged winds were merged together with the TIGCM predictions for corresponding geophysical conditions and converted to a form for inclusion in the VSH model. The coefficients sets for these cases were delivered to AFGL for evaluation.

A total of 106 TIGCM runs have been identified as necessary for the Phase 1 Model development (see Appendix 2.3). These runs will be made during the current fiscal year.

Dr. Roble reported on the progress made in updating and performing validation studies on the TIGCM (see Appendix 2.4). One of the key case studies has involved the detailed one-on-one comparison with total density data along the track of the Air Force satellite containing the SETA instrument. The model was tuned specifically to match the time dependent thermospheric forcings corresponding to the March 22-23 1979 data set. Appendix 2.4 shows the results of this study. Percent differences for measured minus model densities are shown, indicating a standard deviation about the mean of ~9% for dayside data and ~12% for night side data. It should be noted that the TIGCM total densities were corrected by a constant multipicative factor in order to match the measured DC level. This correction factor implies that the total heating rate in the model still needs refinement to match the observed total density structure. Thus work is ongoing to tune the various aeronomical heating and cooling rates to match better the measurements. Nevertheless, the agreement with between the modelled and measured density variations about the global mean are extremely encouraging and indicate that the TIGCM is already providing an improvement over pure semi-empirical models, such as MSIS.

2.2 Plans for the next reporting period.

Plans for the next quarter of effort relate to the work statement given in the original proposal, see Appendix 2.3. Specifically, work on tasks 2-5 will continue.

Work to verify the TIGCM in the altitude region above 250 km will continue. Specific tests involve detailed comparisons with satellite data from a ten day period (days 83021 - 83031) near the end of the Dynamics Explorer mission when full coverage of both hemispheres was possible with all instruments functioning.

Two major case studies are planned, one involving the 10 days of data from the Dynamics Explorer satellite in 1983 and one involving a previous isolated geomagnetic storm study. The Dynamics Explorer data has been provided to Dr. Roble and a series of TIGCM runs are planned that will be extensively analyzed as part of the verification effort. Dr. Roble has prepared a computer animation of the isolated storm study that will be shown at the next quarterly meeting in January. Further work will be carried out to define the VSH library approach. Work will be also carried out to define the TIGCM input stategy for this program, as well as to incorporate data from Dynamics Explorer into the VSH model for a few cases using an objective analysis scheme.

Appendix 2.1

FINAL AGENDA

NEUTRAL ATMOSPHERIC MODEL

QUARTERLY REVIEW

DEPT. OF COMMERCE, BOULDER, CO

21 SEPTEMBER 1989

1.	INTRODUCTION	F. MARCOS	0830
2.	THERMOSPHERE-IONOSPHERE GENERAL CIRCULATION MODEL STATUS	R. ROBLE	0910
3.	VECTOR SPHERICAL HARMONIC MODEL OVERVIEW, PROGRESS, PLANS	T. KILLEEN	0955
	BREAK	----------	1040
4.	LOW AND MIDDLE LATITUDE GEOMAGNETIC STORM RESPONSE MODELING	A. BURNS	1100
5.	OPERATIONAL CONSIDERATIONS	C. TSCHAN	1120
	LUNCH	----------	1200
6.	SPACECOMMAND REQUIREMENTS	J. LIU	1300
7.	DENSITY FROM HISTORICAL DATA BASE	G. DAVENPORT	1345
8.	DISCUSSION ON OPERATIONAL USE OF MODEL	ALL	1400
	ADJOURN	---------	1500

Appendix 2.2

VSH TOP-DOWN DESIGN

Upon each call to the VSH program, the following eight step procedure is carried out. The primary purpose of each step and the subroutine responsible for executing the step is given below.

Each of the indicated subroutines is called from the main controlling routine VALUE. A main driving program is then needed to call VALUE.

1. Determine whether any of the following have changed since last call:
   Latitude, time, TIGCM run, variables requested (INITIAL)

2. Determine if all needed variables have been requested?
   Densities need temperature and mixing ratios.
   Zonal and meridional winds need each other. (INITIAL)

3. If TIGCM run or variables requested have changed:
   Read coefficients for requested variables of desired TIGCM run. Array size is (9 field variables, 3 altitudes, 5 zonal wavenumbers, 25 meridional wavenumbers, 7 Fourier time coefficients). (VSHIN)

4. If time, run, or variables have changed:
   Evaluate Fourier series for the requested time at each variable, altitude, zonal wavenumber, and meridional wavenumber. Coefficient array size is now (9,3,5,25). (TIMETR)

5. If latitude has changed:
   For the requested latitude, find the values of the vector spherical harmonics P, V, and W for each zonal and meridional wavenumber. (BASIS)

6. Evaluate the VSH representation at the requested latitude and longitude for each variable at each altitude:
   For neutral and ion winds, use vector spherical harmonics V and W.
   For other variables, use scalar spherical harmonic P.
   Coefficient array size is now (9,3). (SPACTR)

7. At each altitude, derive densities O, N2, and O2.
   Coefficient array size is now (12,3) (DENSITY)

8. If a specific altitude was requested (rather than a pressure surface), interpolation or extrapolation is necessary:
   For temperature, assume a Bates fit.
   For densities, assume a linear fit in their logarithms.
   For other variables, assume a quadratic fit.
   However, if extrapolation is needed above the highest pressure surface, assume that winds and temperature have reached their asymptotic values. (ALTTR)

MODIFICATIONS IN PROGRESS

The vertical interpolation procedure (step 8) will be changed into a Chebyshev function representation. This modification will allow a more accurate representation in the vertical of tidal effects.

The Fourier representation in time (step 4) will also be changed into a Chebyshev basis. This modification will allow a more accurate representation of magnetic storm conditions (as the restriction to periodic boundary conditions will be eliminated).

TIGCM RUNS AVAILABLE FOR VSH

1. Solar maximum winter solstice conditions with average geomagnetic activity (Kp=3, Ap 20, F10.7=220, Cross-cap potential 60kV)

2. Solar minimum winter solstice conditions with average geomagnetic activity (Kp=3, Ap 20, F10.7=120, Cross-cap potential 30kV)

3. Solar minimum equinox conditions with average geomagnetic activity (Kp=3, Ap 20, F10.7=120, Cross-cap potential 30kV)

4. Solar maximum solstice conditions with average magnetic activity By positive conditions

5. Solar maximum solstice conditions with average magnetic activity By negative conditions

6. Model transformed into magnetic coords. for solar maximum at solstice with average magnetic activity By negative conditions

7. Model transformed into magnetic coords. for solar maximum at solstice with average magnetic activity By positive conditions

8. Solar maximum, Dec solstice avg activity with BY=0,hp=11,x-cap=60kV is merged with DE-2 data. The DE-2 winds are for Kp <= 3.0, By > 0.0 with the high-latitude data (>35 degrees) in geomagnetic coords. and the low latitude data in geographic.

9. Solar maximum, Dec solstice avg activity with BY=0,hp=11,x-cap=60kV is merged with DE-2 data. The DE-2 winds are for Kp > 3.0, By > 0.0 with the high-latitude data (>35 degrees) in geomagnetic coords. and the low latitude data in geographic.

10. Solar maximum, Dec solstice avg activity with BY=0,hp=11,x-cap=60kV is merged with DE-2 data. The DE-2 winds are for Kp <= 3.0, By < 0.0 with the high-latitude data (>35 degrees) in geomagnetic coords. and the low latitude data in geographic.

11. Solar maximum, Dec solstice avg activity with BY=0,hp=11,x-cap=60kV is merged with DE-2 data. The DE-2 winds are for Kp > 3.0, By < 0.0 with the high-latitude data (>35 degrees) in geomagnetic coords. and the low latitude data in geographic.

12. Solar maximum solstice conditions with low geomagnetic activity (Kp=1, HP=3, F10.7=220, Cross-cap potential 30kV)

13. Solar maximum solstice condition with average geomagnetic activity (Kp=3, HP= 11, F10.7=220, Cross-cap potential 60kV)

14. Solar maximum solstice conditions with average geomagnetic activity (Kp=5, HP= 33, F10.7=220, Cross-cap potential 90kV)

VSH VARIABLE DICTIONARY

ALT	REAL	Requested altitude or pressure surface (1, 2, or 3)
FLDDIM	INTEGER	Dimensioned number of variables (excluding densities)
FLDMAX	INTEGER	Number of variables actually used (excluding densities)
GCOLAT	REAL	Requested geographical colatitude
GLON	REAL	Requested geographical longitude
GETDENS	LOGICAL	.TRUE. if a call to DENSITY is needed
HRDIM	INTEGER	Dimensioned number of time periods in coefficient data
HRMAX	INTEGER	Number of time periods represented in coefficient data
IPRINT	INTEGER	A debug print control; not presently in use
IRUN	INTEGER	Requested TIGCM run number
LASTLAT	REAL	Requested latitude on previous call
LASTRUN	INTEGER	Requested TIGCM run on previous call
LASTUSI	LOGICAL(12)	Requested USING values on previous call
LASTTIM	REAL	Requested UT on previous call
MDIM	INTEGER	Dimensioned number of zonal wavenumbers
MMAX	INTEGER	Number of zonal wavenumbers actually used this run
NEWLAT	LOGICAL	.TRUE. if a new latitude has been requested
NEWTIM	LOGICAL	.TRUE. if a new UT has been requested
NEWRUN	LOGICAL	.TRUE. if a new run has been requested
ONES	INTEGER	IRUN modulo 10
PBAR	REAL(MDIM+1,NDIM+1)	Scalar spherical harmonic P
PHASE	REAL	Phase angle
SOLAR	INTEGER	0 or 1 depending on solar max or solar min
STVSH	REAL(ZDIM,VARDIM)	Coefficient array following space and time transformation
TDIM	INTEGER	Dimensioned number of time periods
TENS	INTEGER	Integer(IRUN/10)
TVSH	REAL(FLDDIM,ZDIM,MDIM,NDIM)	Coefficient array following time transformation
TMAX	INTEGER	Number of time periods actually used
USING	LOGICAL(12)	.TRUE. for a variable if it has been requested
UT	REAL	Requested universal time
UTHR	REAL(HRDIM)	UT's specified in coefficeint file
VARDIM	INTEGER	Dimensioned number of variables including densities
VARMAX	INTEGER	Number of variables including densities actually used
VBAR	REAL(MDIM+1,NDIM+1)	Vector spherical harmonic V
VSH	REAL(FLDDIM,ZDIM,MDIM,NDIM,TDIM)	Coefficient array as read in from data files
XALT	REAL(ZDIM)	Altitudes specified in coefficient file
WBAR	REAL (MDIM+1,NDIM+1)	Vector spherical harmonic W

COEFFICIENT DATA FILES

Currently, 14 runs of the TIGCM model are available to the VSH program. Each is stored in an identical binary unformatted form in files RUN01.DAT through RUN14.DAT. For each of the 9 field variables, there are two records: a header record and the data record.

The header record contains information on the truncation level of the coefficient data as well as their altitudes and universal times. The data is stored in the sequence: MMAX, NMAX, TMAX, ZMAX, HRMAX, (UTHR(I), I=1,HRMAX), (XALT(I), I=1,ZMAX).

The data record is stored as ((((VSH(VAR,Z,M,N,T), Z=1,ZMAX), M-1,MMAX), N=1,NMAX), M=1,MMAX)

VSH INPUT/OUTPUT VARIABLES

OUTPUT VARIABLES

Name	Type	Description
OUTPUT(12)	REAL	the array of output variables: zonal neutral wind (U) meridional neutral wind (V) neutral temperature (T) meridional ion drift ,(Ui) zonal ion drift (Vi) vertical neutral wind (W) height of the contant pressure level (ALT) atomic oxygen mass mixing ratio molecular nitrogen mass mixing ratio atomic oxygen number density molecular oxygen number density molecular nitrogen number density

INPUT VARIABLES

Name	Type	Description
USING(12)	LOGICAL	an array of 12 logical variables (.true. or .false.) corresponding to each of the above 12 variables; setting a value to .false. eliminates calculation of of that variable (to reduce computational time)
GLON	REAL	geographic longitude GLON (degrees)
GCOLAT	REAL	geographic co-latitude GCOLAT (degrees)
UT	REAL	Universal Time UT (hours)
ALT	REAL	altitude (km) (between 130 and 600 km); or a pressure surface (indicated by a 1, 2, or 3): ALT= 1: denotes z= -4 surface (~120km) ALT= 2: denotes z= -1 " (~185km) ALT= 3: denotes z= +1 " (~350km) (For solar minimum cases, z=-4, -2, and +2)
IRUN	INTEGER	the particular TIGCM run:

Appendix 2.3

Neutral Model Development Schedule

- Program broken down by 13 Tasks in Statement of Work
- Years refer to Fiscal Years, starting in FY 1989
- Year 1: Complete Task1 and start tasks 2, 3, 4, and 5
- Year 2: Complete Tasks 2, 3, 4, and 5 and start tasks 6 and 7
- Year 3: Complete Tasks 6, 7, 8, and 9 and start task 10
- Year 4: Complete Tasks 10 and 11
- Year 5: Complete Tasks 12 and 13.
- Half-yearly design reviews will be held at the University of Michigan, NCAR and AFGL on a rotating basis. Quarterly visits by AF monitors will also be supported at the University of Michigan or NCAR

Neutral Model Development Schedule

Year 1.

- Task 1: Program Definition:
  U of M and NCAR to develop a detailed program schedule for the 5-year effort - present major program milestones in the first semi-annual report
- Task 2: TIGCM Verification:
  Verify new model with satellite, rocket, and ground-based predictions
- Task 3: Finalize development of new TIGCM for the NTM Phase I
- Task 4: Develop algorithms for the NTM. Vector Spherical Harmonic Expansion and Objective Analysis
- Task 5: Sensitivity study of the aeronomic scheme used in the TIGCM Impacts of uncertainties in rate coefficients, solar EUV, F107 fluxes, auroral inputs.

Neutral Model Development Schedule

Year 2.

- Report on Tasks 1-5
- Task 6: *Perform TIGCM runs to provide data base for use in the* Phase I (250 - 1500 km) operational model
- Task 7: Merger of NTM with MSIS and available experimental data. Extend NTM beolw 250 km using MSIS. Develop objective analysis scheme to incorporate experimental data based on existing optimal estimator algorithms. Incorporate DE, and SETA data sets
- Delivery of NTM (mk I) at end of Fiscal Year (250 - 1500 km)

Neutral Model Development Schedule

Year 3.

- Report on Tasks 6, 7
- Start and finish Task 8:
  Perform TIGCM runs to generate data for Phase II NTM (includes 140 - 250 km region). Validation and test case studies
- Start and finish Task 9: Develop NTM algorithms to represent thermospheric properties in 140- 250 km region
- Start Task 10: Perform TIGCM runs for the Phas III NTM (includes 90 - 1500 km range). Validation and test studies
- Delivery of NTM (mk II) at end of Fiscal Year (140 - 1500 km)

NTM - AFGL/AWS, Boulder 5/8/4 TLK 4

Neutral Model Development Schedule

Year 4.

- Report on Tasks 10 and 11
- Task 10: Update NTM with TIGCM runs for 90-140 km region
- Incorporate any new data sets (ADS spacecraft?)
- Task 11: Feasibility of operational TIGCM. Work will begin on adapting an operational and validated TIGCM for use on ab Air Force computer
- Delivery of NTM (mk III) at end of Fiscal Year (90 - 1500 km)

Neutral Model Development Schedule

Year 5.

- Report on Tasks 12 and 13
- Task 12: Deliver Operational TIGCM
- Task 13: Continued validation and experimental data ingestion. Maintenance of NTM

Neutral Model Development Schedule

Year 1. - Detail

- Late start - March 27 1989 start date
- UofM subcontract to NCAR
- Personnel at UofM: division of *responsibilities*
  - Dr. Killeen: VSH and Objective analysis, ingestion of spacecraft data
  - Dr. Johnson: TIGCM Validation studies
  - Mr. Rob Raskin: programmer, VSH library approach
  - Captain Ken Reese: Ground-based data ingestion
- Personnel at NCAR: division of responsibilities
  - Dr. Roble: Finalization of TIGCM for NTM mk. 1
  - Mr. Ben Foster: Graphical displays, networking
- Major Milestone:
  First semi-annual report (August 1989). Presentation of detailed program. Status of VSH/Objective analysis algcrithms, TIGCM Validation, etc.

Neutral Model Development Schedule

Year 1. - Detail continued

End of FY :

- Validated TIGCM above 250 km - extensive case study validation tests
- Design and development of VSH scheme to access and store TIGCM predictions
- Development of objective analysis scheme to incorporate experimental data into NTM
- Basic NTM algorithm written ??

Neutral Model Development Schedule

VSH Progress

End of Fiscal year:

- Delivered initial bench-test model routine to AFGL
- Improvement in speed of routine (factor of 6)
- Objective analysis using Dynamics Explorer winds successfuly implemented
- Initial set of TIGCM runs for Phase I identified

Phase I TIGCM runs

Levels of Geomagnetic Activity:	5
Season:	4
Solar Flux:	5
Substorm simulations:	6

Total number of runs: 5 x 4 x 5 + 6 = 106

Appendix 2.4

NCAR THERMOSPHERE/IONOSPHERE GENERAL CIRCULATION MODEL (TIGCM)

- Primitive equations of dynamic meteorology adapted to thermospheric heights.
- Eulerian model of the ionosphere.
- Horizontal grid 5° latitude × 5° longitude, geographic.
- Vertical grid - 25 constant pressure surfaces, 2 grid points per scale height, 95 to 500 km.
- Time step 150 or 300 S.

INPUT

- Solar EUV and UV radiation 5 to 250 nm.
- Empirical ionospheric convection and auroral particle precipitation models.
- Structure of upward propagating tides from middle atmosphere.

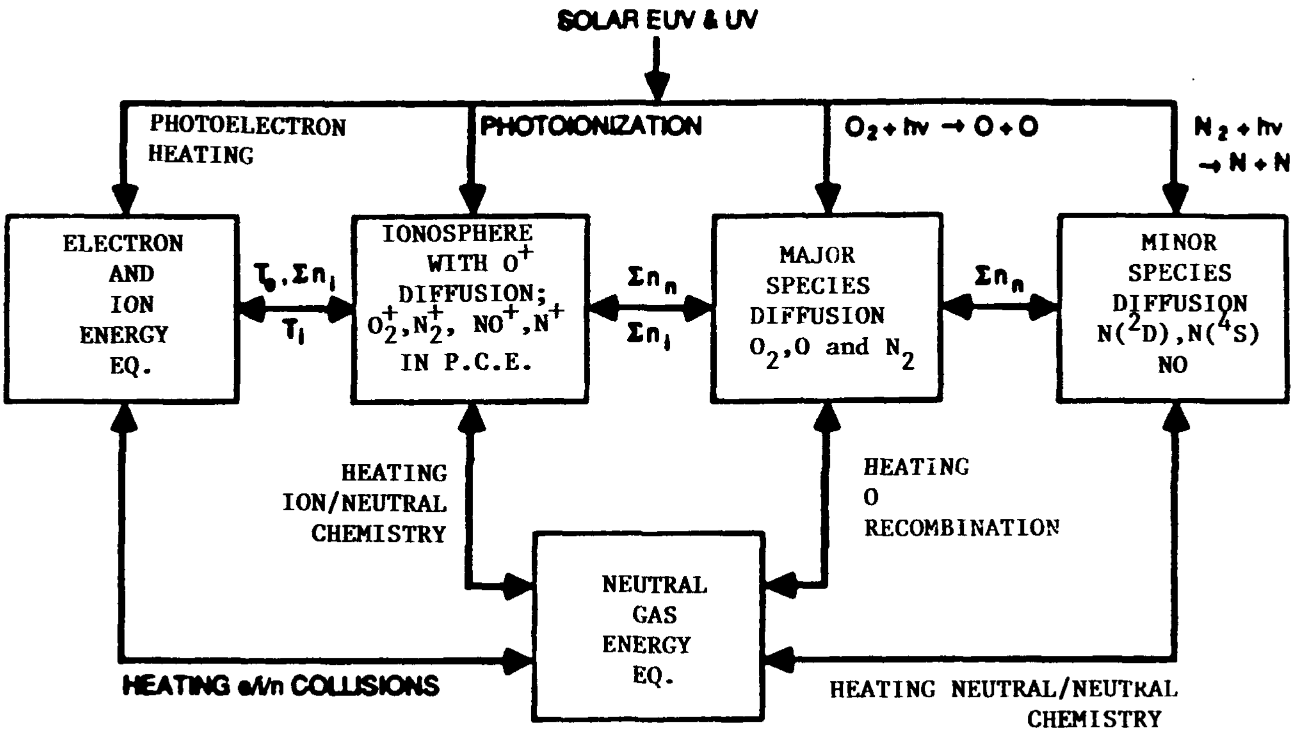

SOLAR EUV & UV
PHOTOELECTRON HEATING
PHOTOIONIZATION
$O_2 + h\nu \rightarrow O + O$
$N_2 + h\nu \rightarrow N + N$
ELECTRON AND ION ENERGY EQ.
$T_e, \Sigma n_i$
T_i
IONOSPHERE WITH O^+ DIFFUSION; O_2^+, N_2^+, NO^+, N^+ IN P.C.E.
Σn_n
Σn_i
MAJOR SPECIES DIFFUSION O_2, O and N_2
Σn_n
MINOR SPECIES DIFFUSION $N(^2D), N(^4S)$ NO
HEATING ION/NEUTRAL CHEMISTRY
HEATING O RECOMBINATION
NEUTRAL GAS ENERGY EQ.
HEATING e/i/n COLLISIONS
HEATING NEUTRAL/NEUTRAL CHEMISTRY

Fig. 6

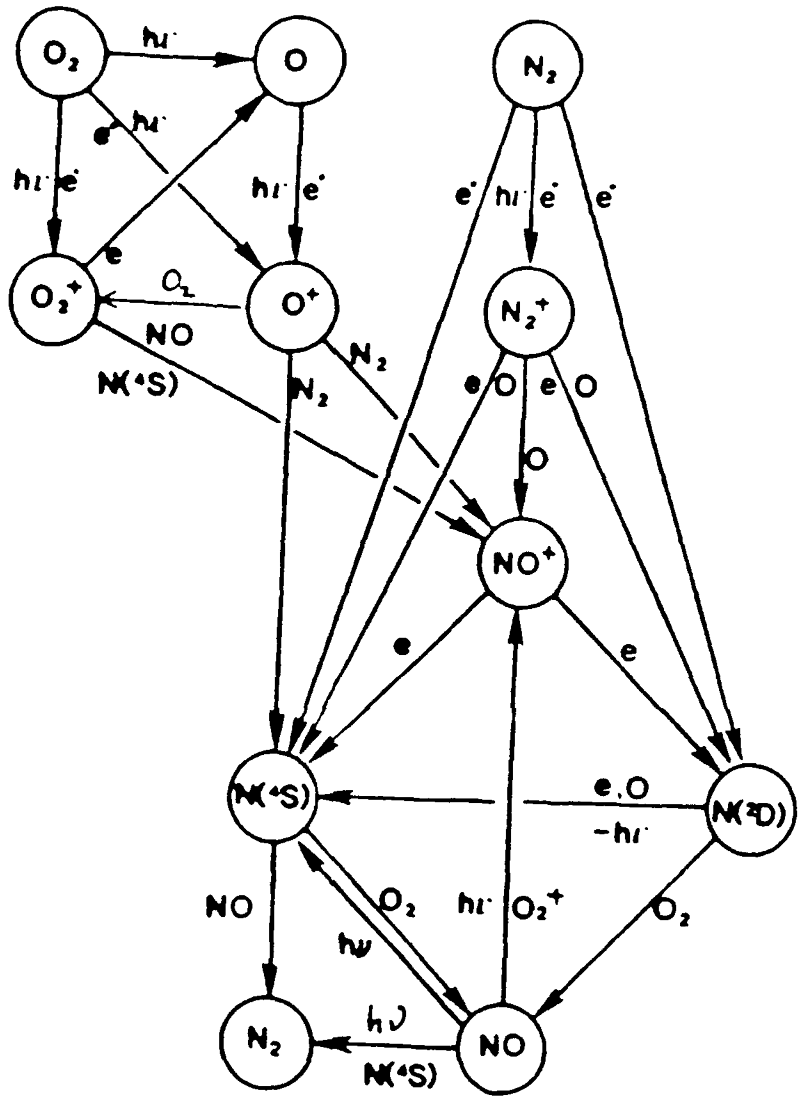


Fig. 7

F10.7 FLUX: 81281-89103

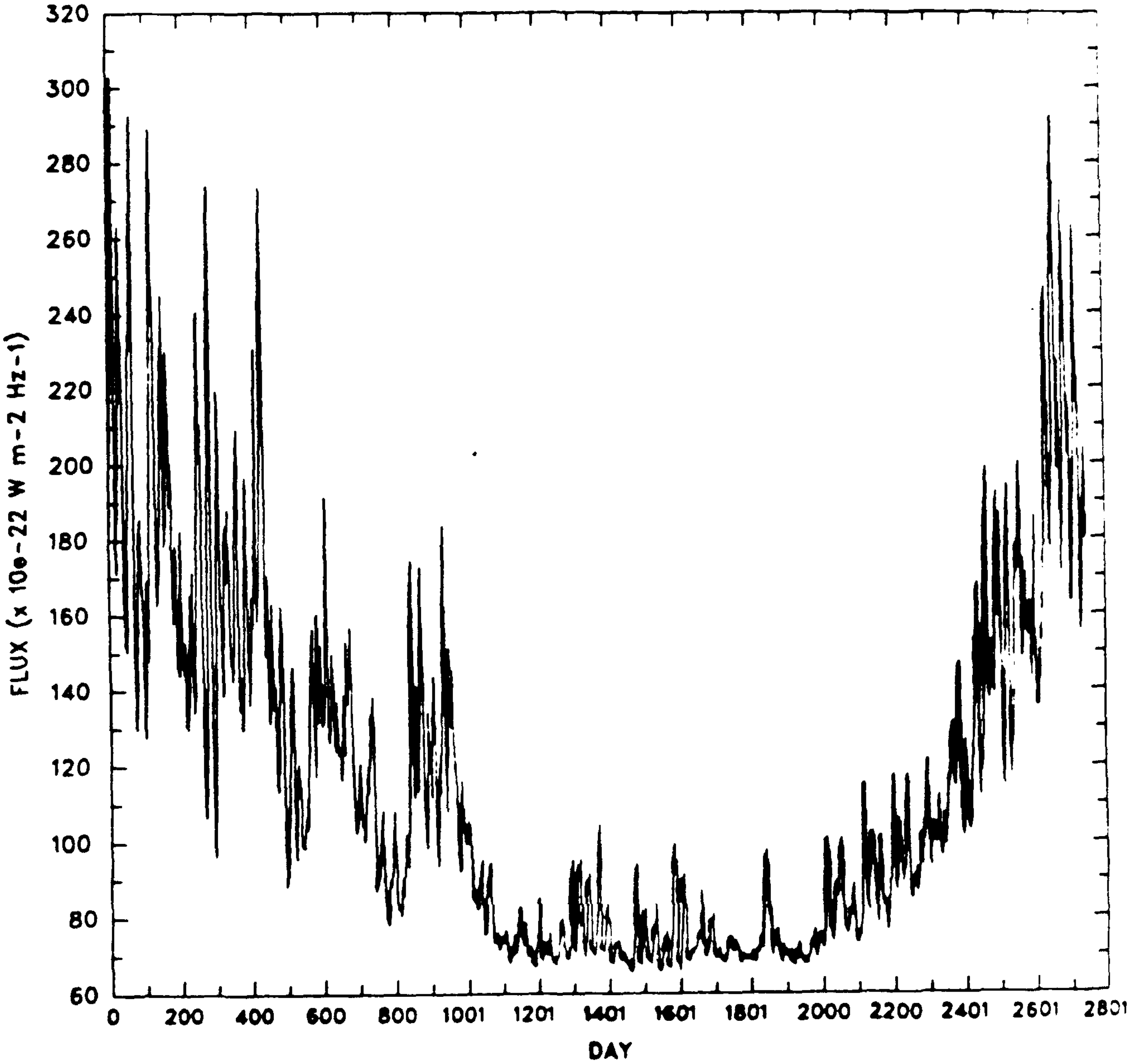


Fig. 8

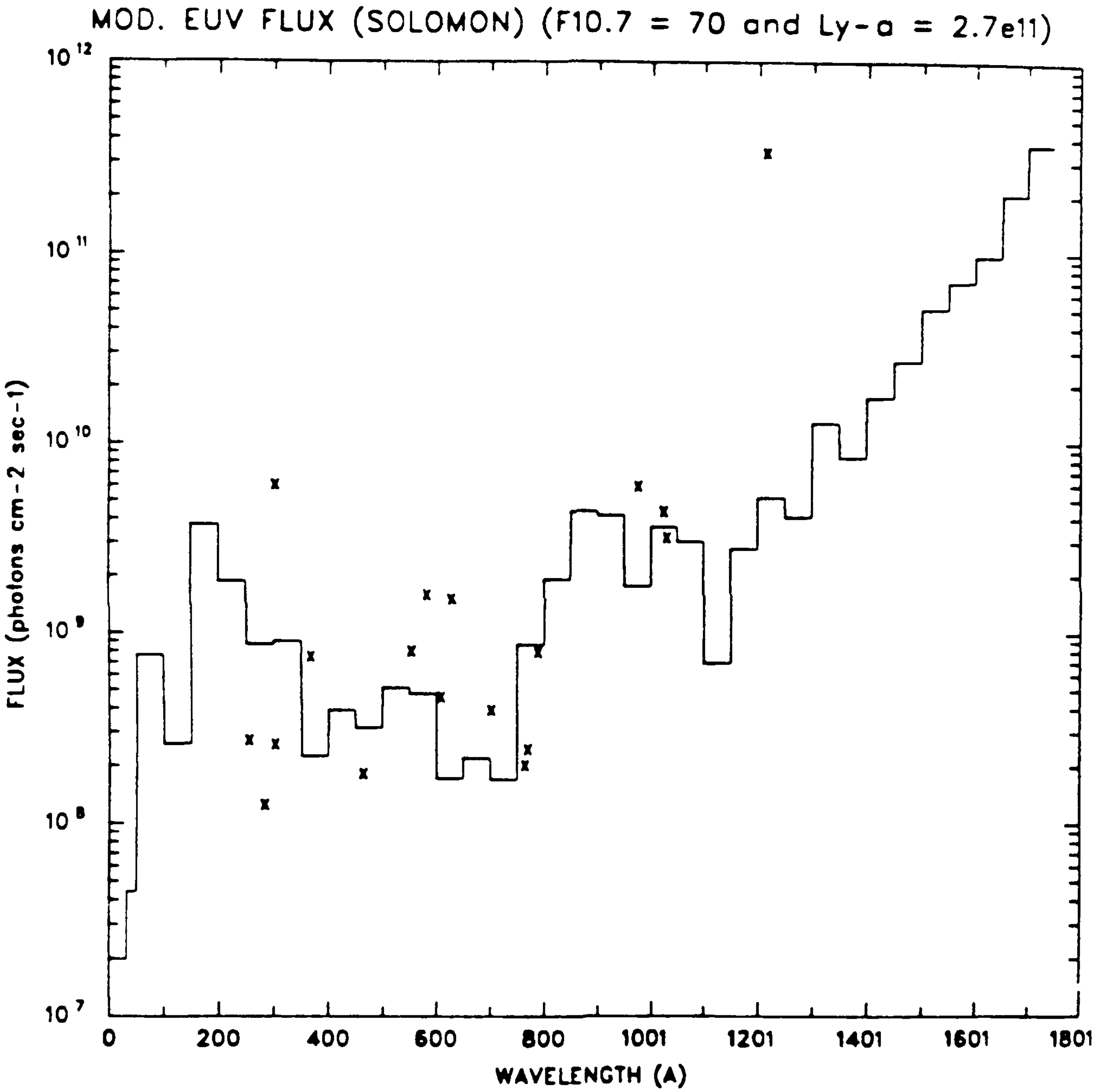

MOD. EUV FLUX (SOLOMON) (F10.7 = 70 and Ly-a = 2.7e11)
FLUX (photons cm-2 sec-1)
WAVELENGTH (A)
0
200
400
600
800
1001
1201
1401
1601
1801

Fig. 9

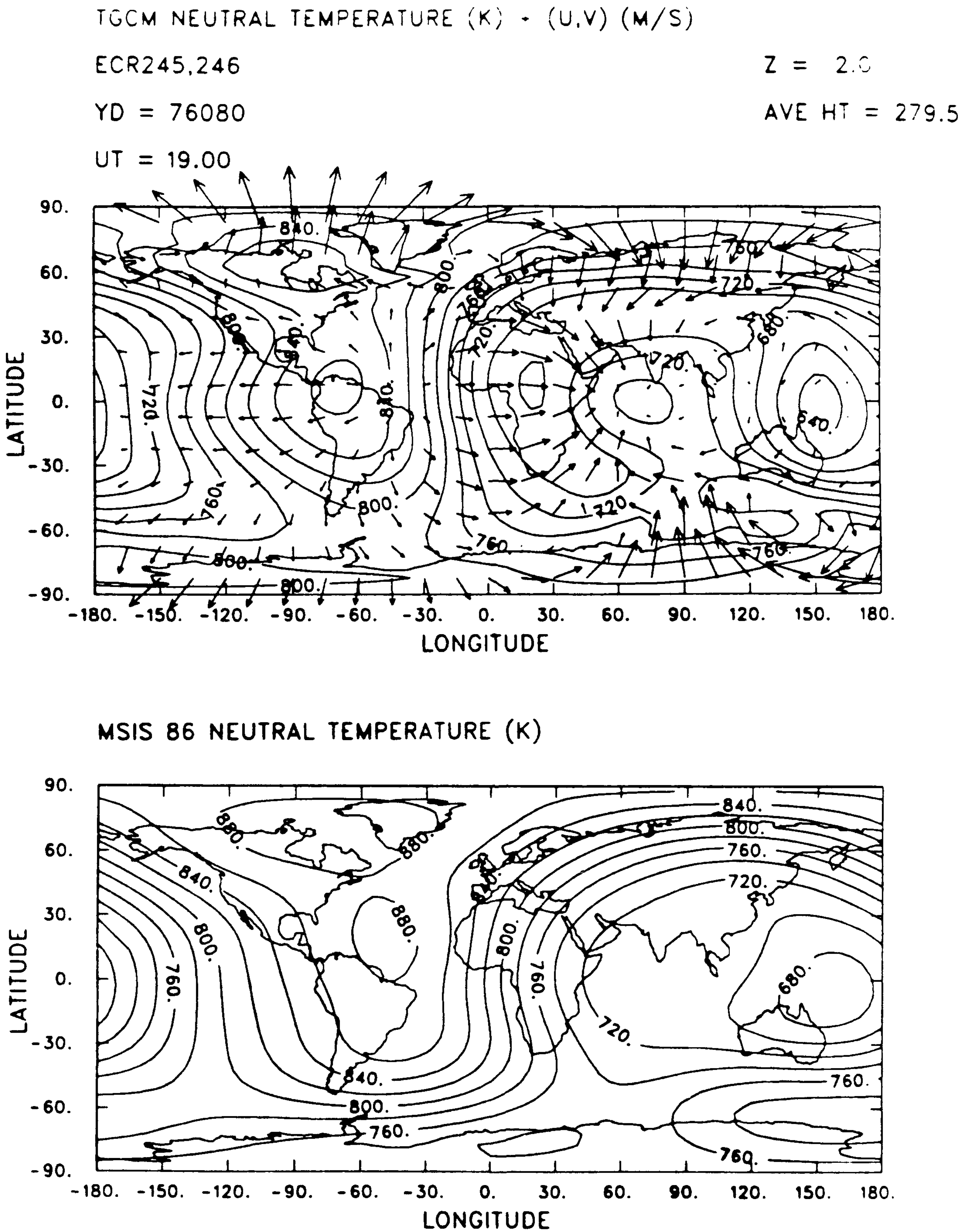

TGCM NEUTRAL TEMPERATURE (K) + (U,V) (M/S)
ECR245,246
Z = 2.0
YD = 76080
AVE HT = 279.5
UT = 19.00
LATITUDE
LONGITUDE
MSIS 86 NEUTRAL TEMPERATURE (K)
LATITUDE
LONGITUDE

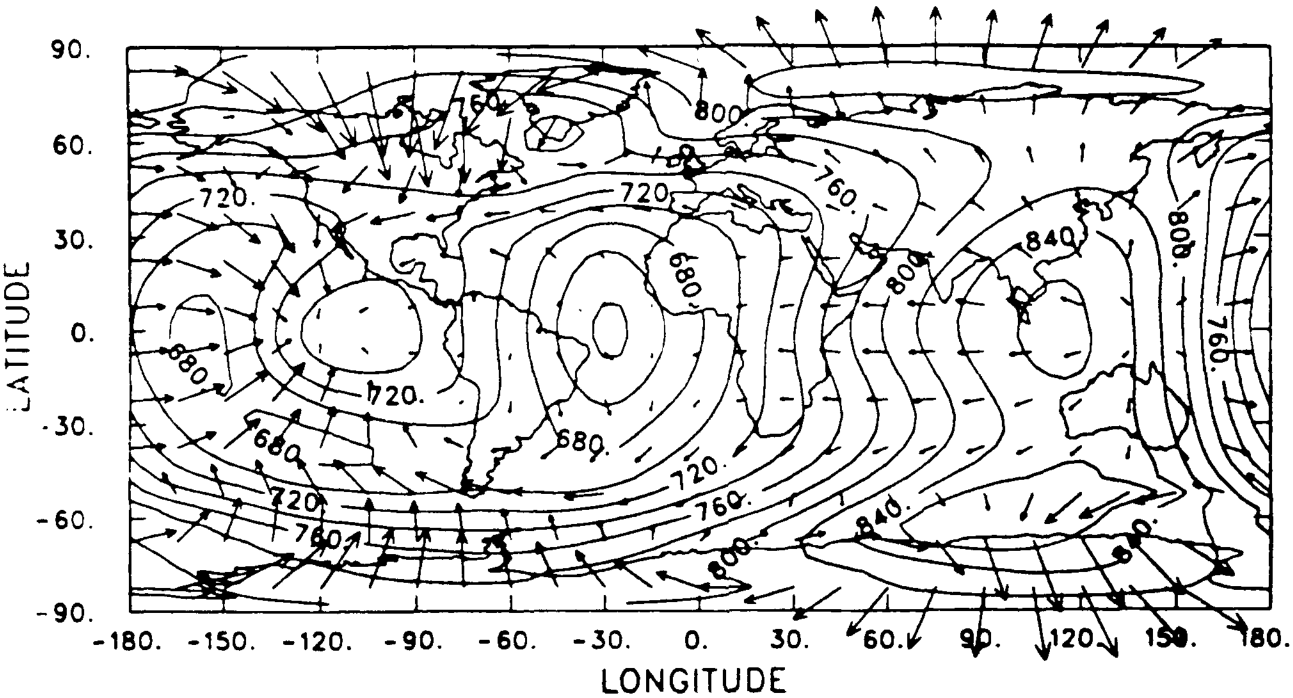
Fig. 10

TGCM NEUTRAL TEMPERATURE (K) + (U,V) (M/S)

ECR245,246 Z = 2.0

YD = 76081 AVE HT = 279.9

UT = 7.00



MSIS 86 NEUTRAL TEMPERATURE (K)

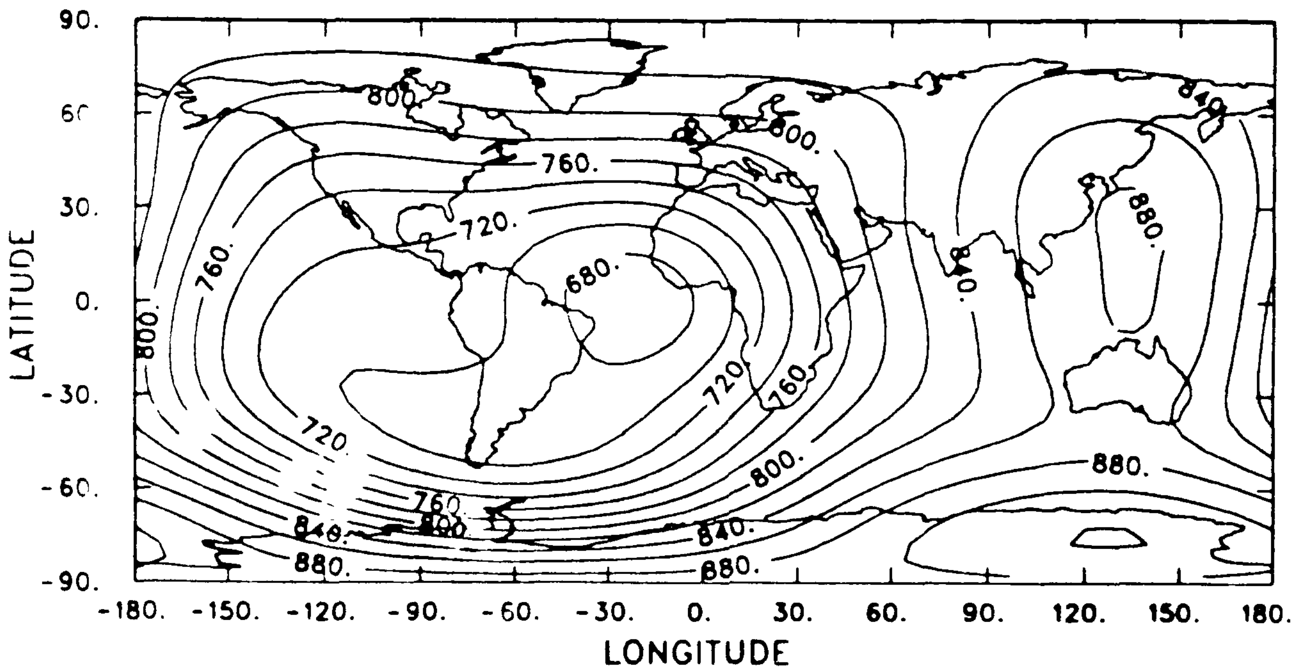


Fig. 11

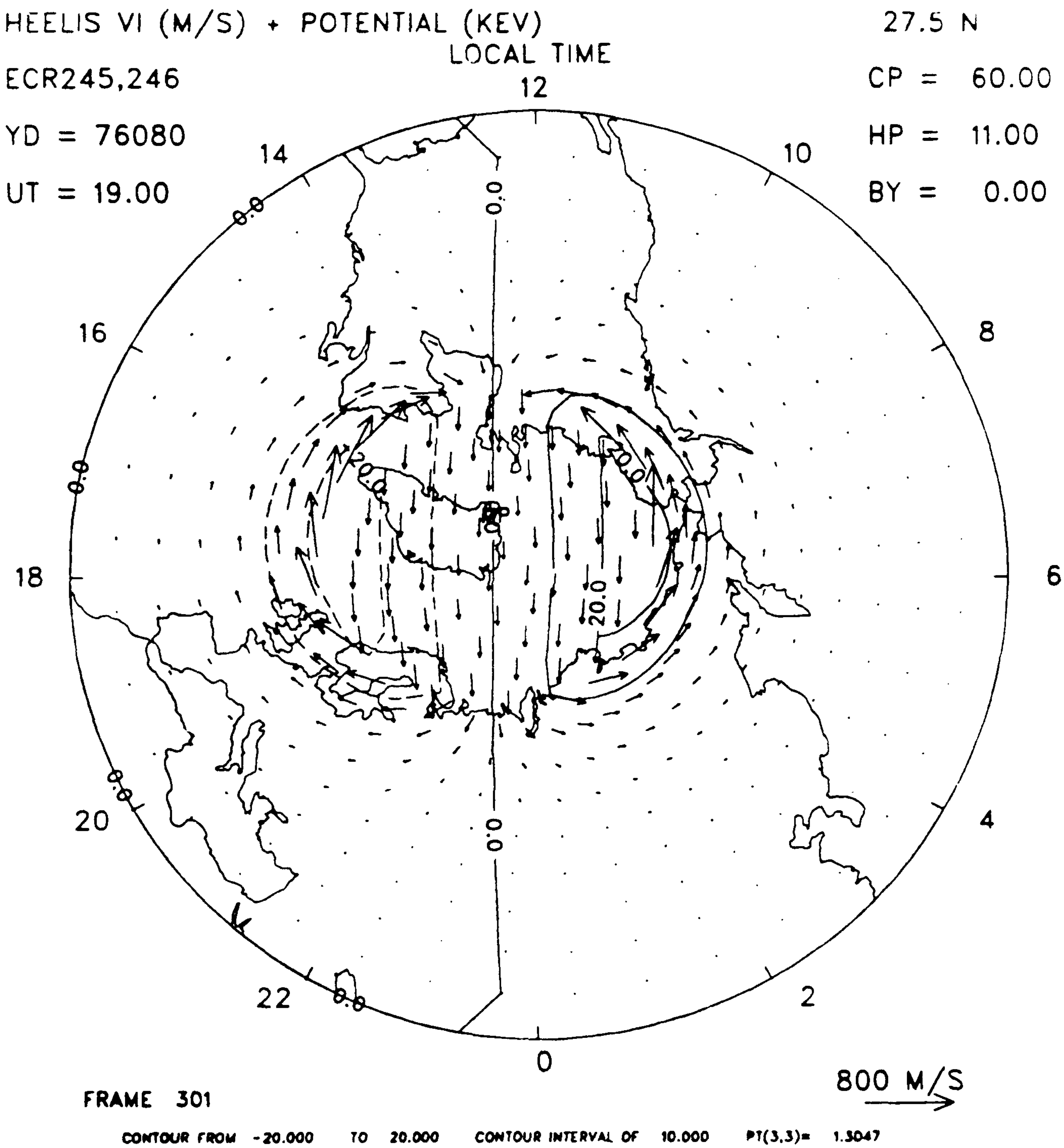

HEELIS VI (M/S) + POTENTIAL (KEV)
ECR245,246
YD = 76080
UT = 19.00
27.5 N
CP = 60.00
HP = 11.00
BY = 0.00
LOCAL TIME
12
14
10
16
8
18
6
20
4
22
2
0
0.0
20.0
-20.0
800 M/S
FRAME 301
CONTOUR FROM -20.000 TO 20.000 CONTOUR INTERVAL OF 10.000 PT(3,3)= 1.3047

Fig. 12

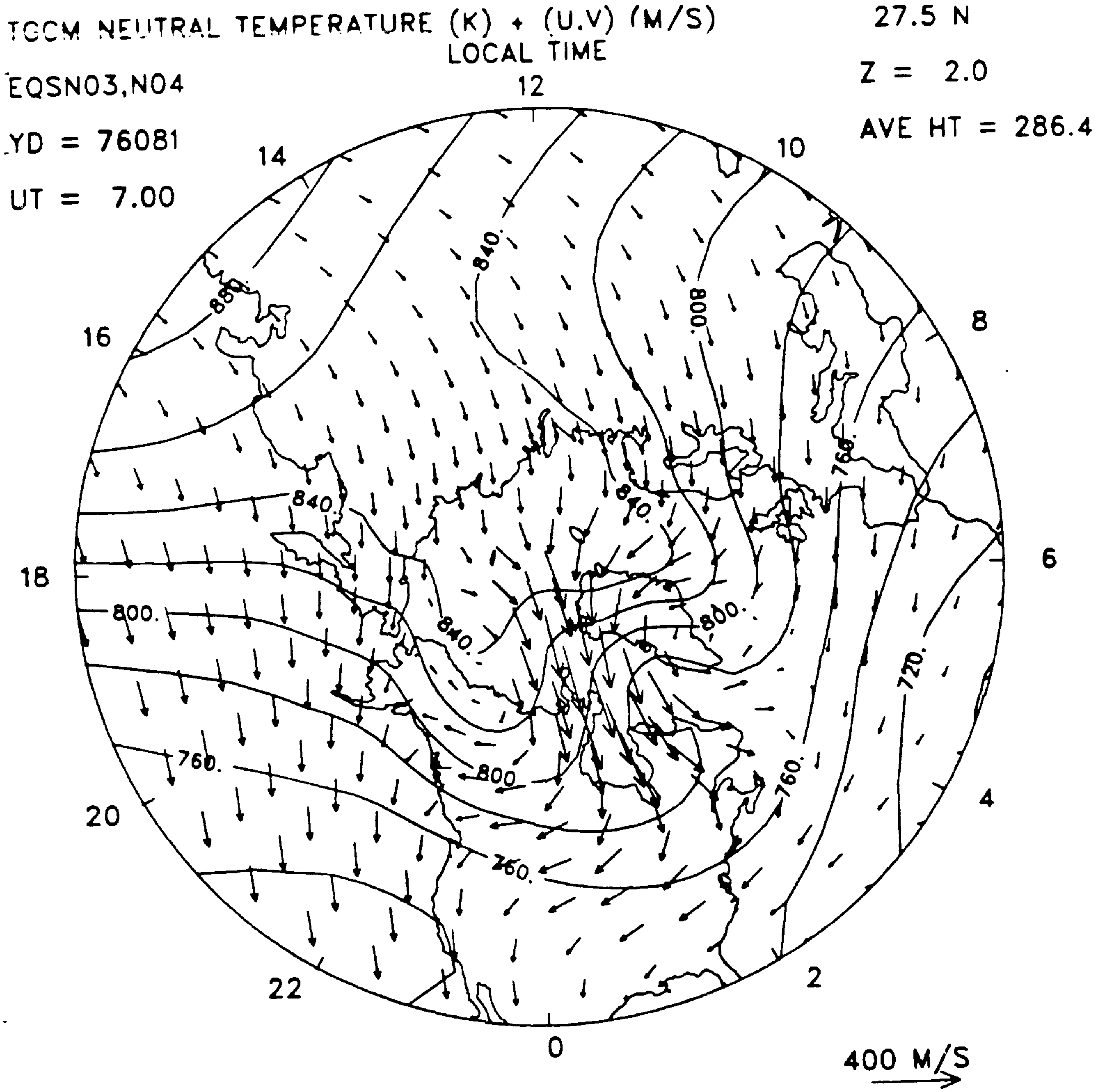

TGCM NEUTRAL TEMPERATURE (K) + (U,V) (M/S)
27.5 N
LOCAL TIME
EQSN03,N04
Z = 2.0
YD = 76081
AVE HT = 286.4
UT = 7.00
12
14
10
16
8
18
6
20
4
22
2
0
840.
880.
800.
760.
720.
400 M/S

Fig. 13

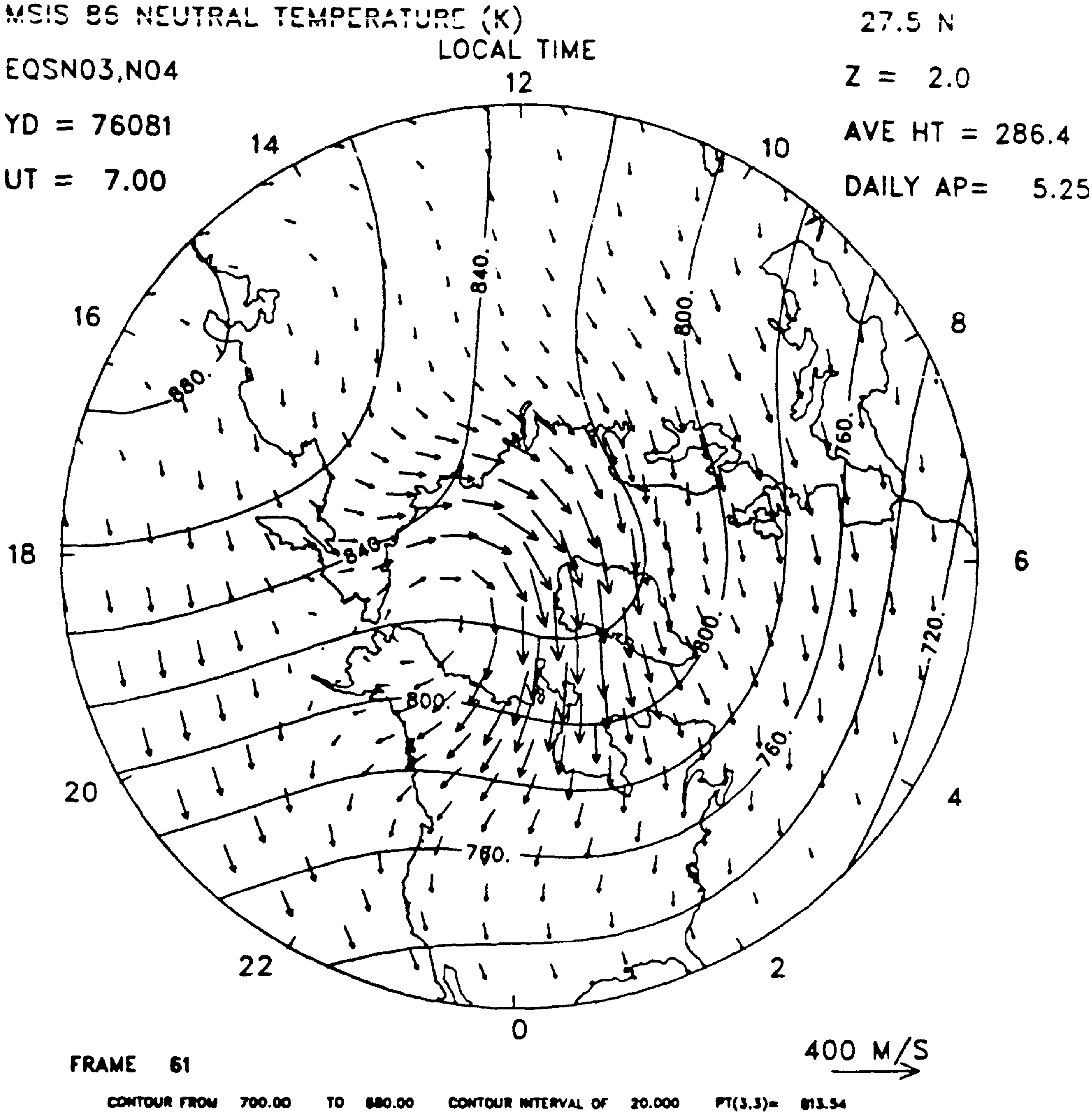

MSIS 86 NEUTRAL TEMPERATURE (K)
27.5 N
LOCAL TIME
EQSN03,N04
YD = 76081
UT = 7.00
Z = 2.0
AVE HT = 286.4
DAILY AP= 5.25
12
14
10
16
8
18
6
20
4
22
2
0
880.
840.
800.
760.
720.
400 M/S
FRAME 61
CONTOUR FROM 700.00 TO 880.00 CONTOUR INTERVAL OF 20.000 PT(3,3)= 813.54

Fig. 14

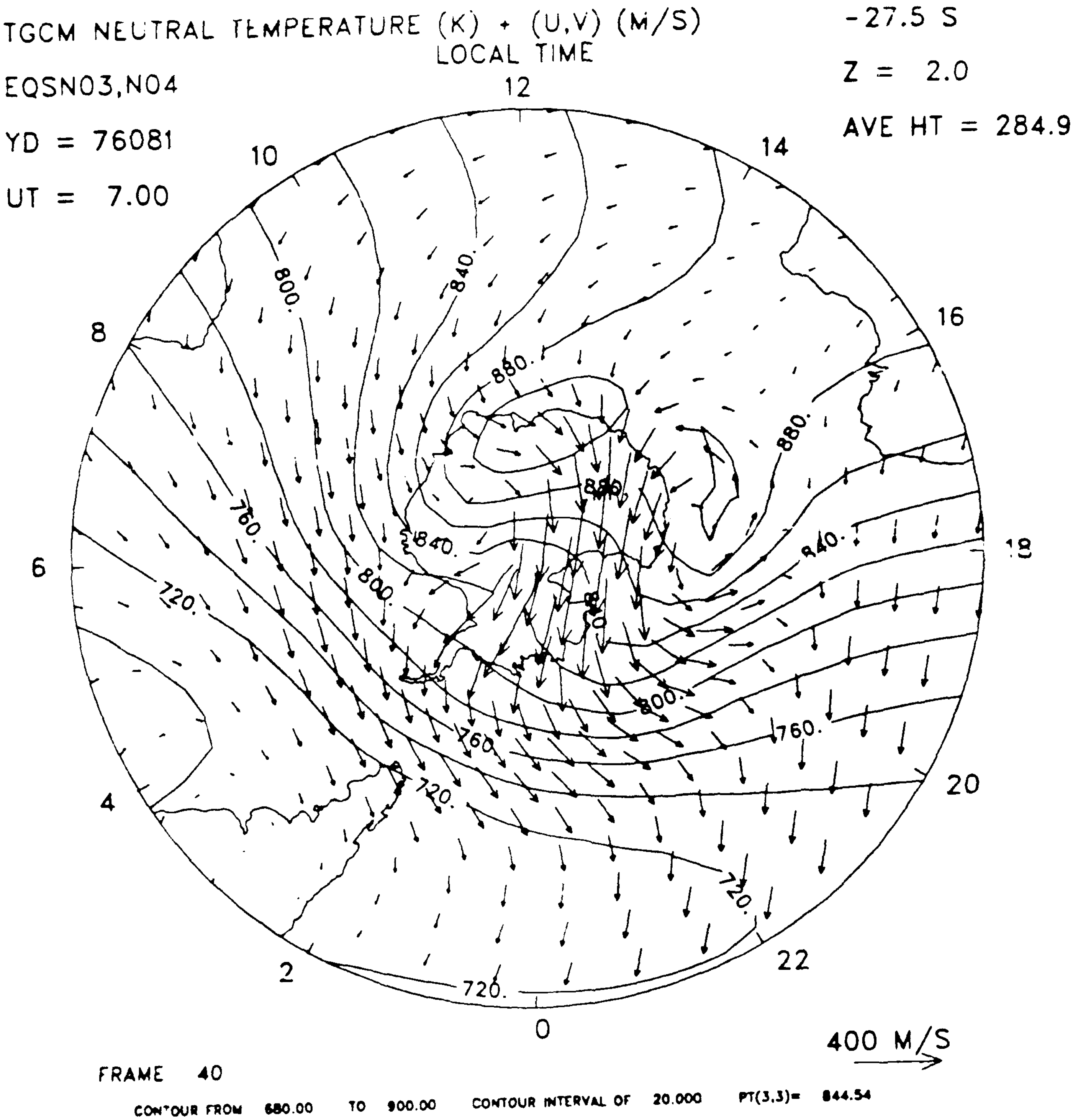
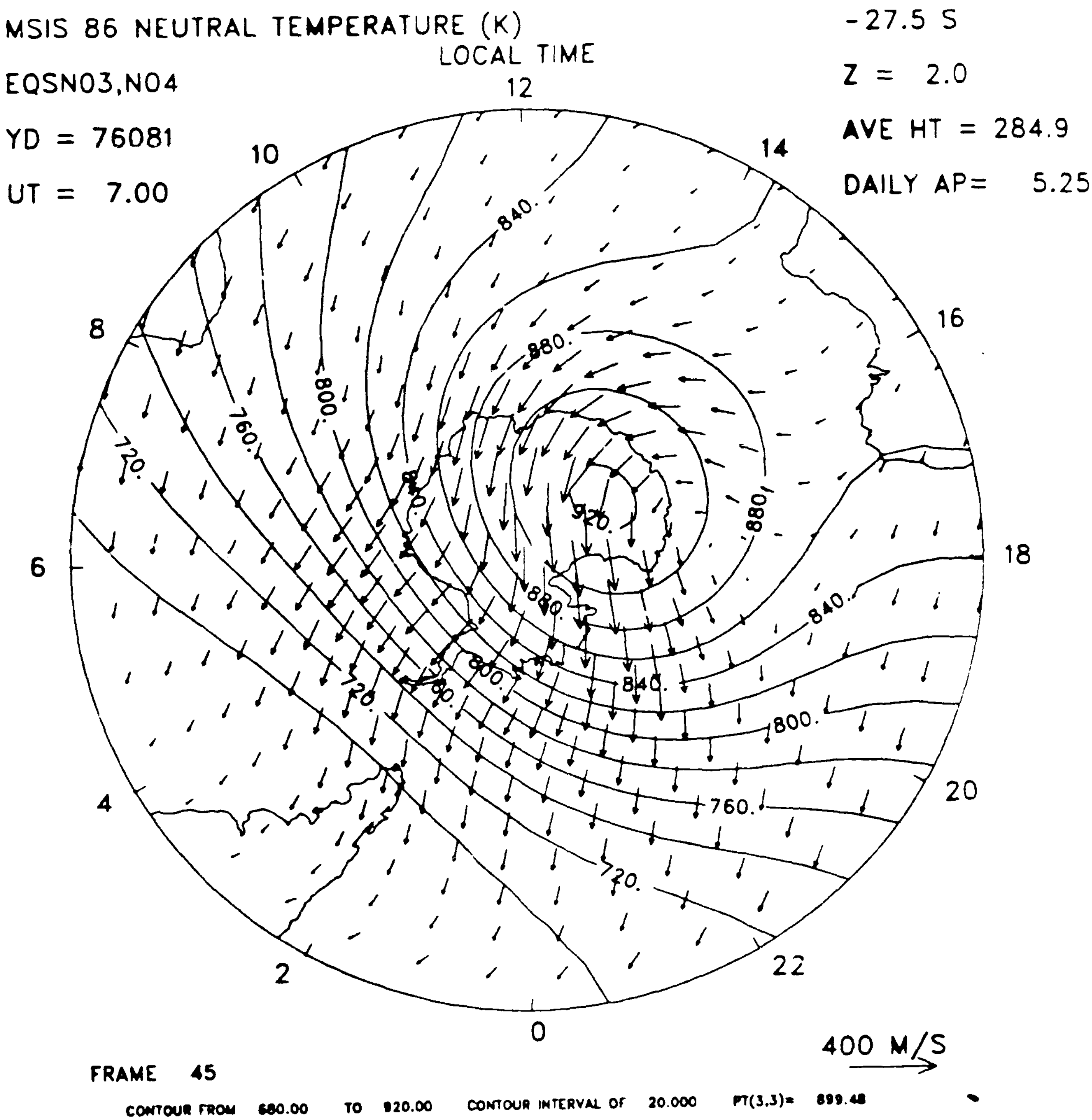

TGCM NEUTRAL TEMPERATURE (K) + (U,V) (M/S)
-27.5 S
LOCAL TIME
EQSN03,N04
Z = 2.0
YD = 76081
AVE HT = 284.9
UT = 7.00
12
10
14
8
16
6
18
4
20
2
22
0
800.
840.
880.
760.
720.
400 M/S
FRAME 40
CONTOUR FROM 680.00 TO 900.00 CONTOUR INTERVAL OF 20.000 PT(3,3)= 844.54

Fig. 15



MSIS 86 NEUTRAL TEMPERATURE (K)
EQSN03,N04
YD = 76081
UT = 7.00
LOCAL TIME
-27.5 S
Z = 2.0
AVE HT = 284.9
DAILY AP= 5.25
12
14
16
18
20
22
0
2
4
6
8
10
840.
880.
920.
800.
760.
720.
400 M/S
FRAME 45
CONTOUR FROM 680.00 TO 920.00 CONTOUR INTERVAL OF 20.000 PT(3,3)= 899.48

Fig. 16

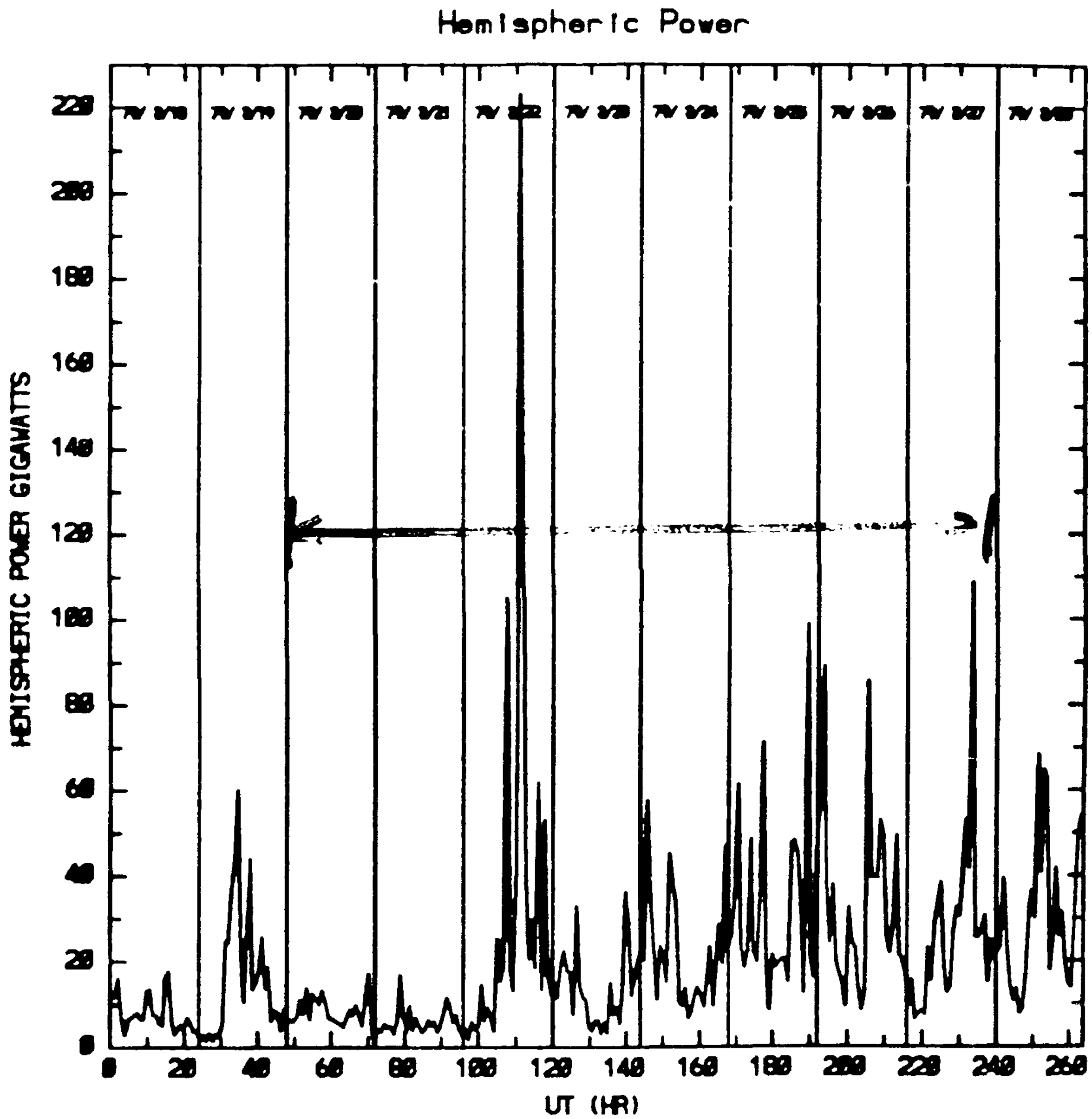

Hemispheric Power
HEMISPHERIC POWER GIGAWATTS
UT (HR)
0
20
40
60
80
100
120
140
160
180
200
220
240
260

Fig. 17

Filtered Cross-Tail Potential

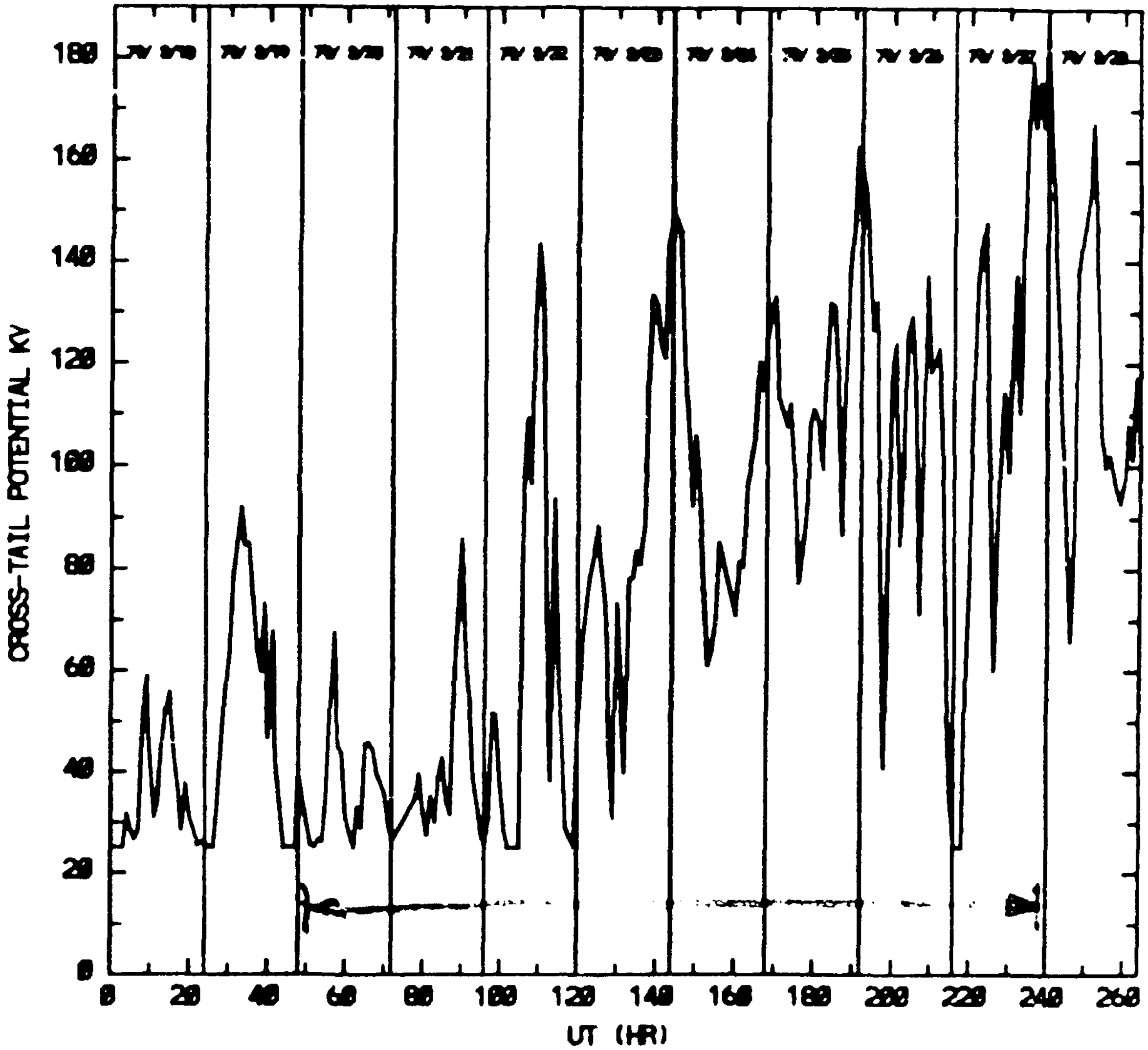


Fig. 18

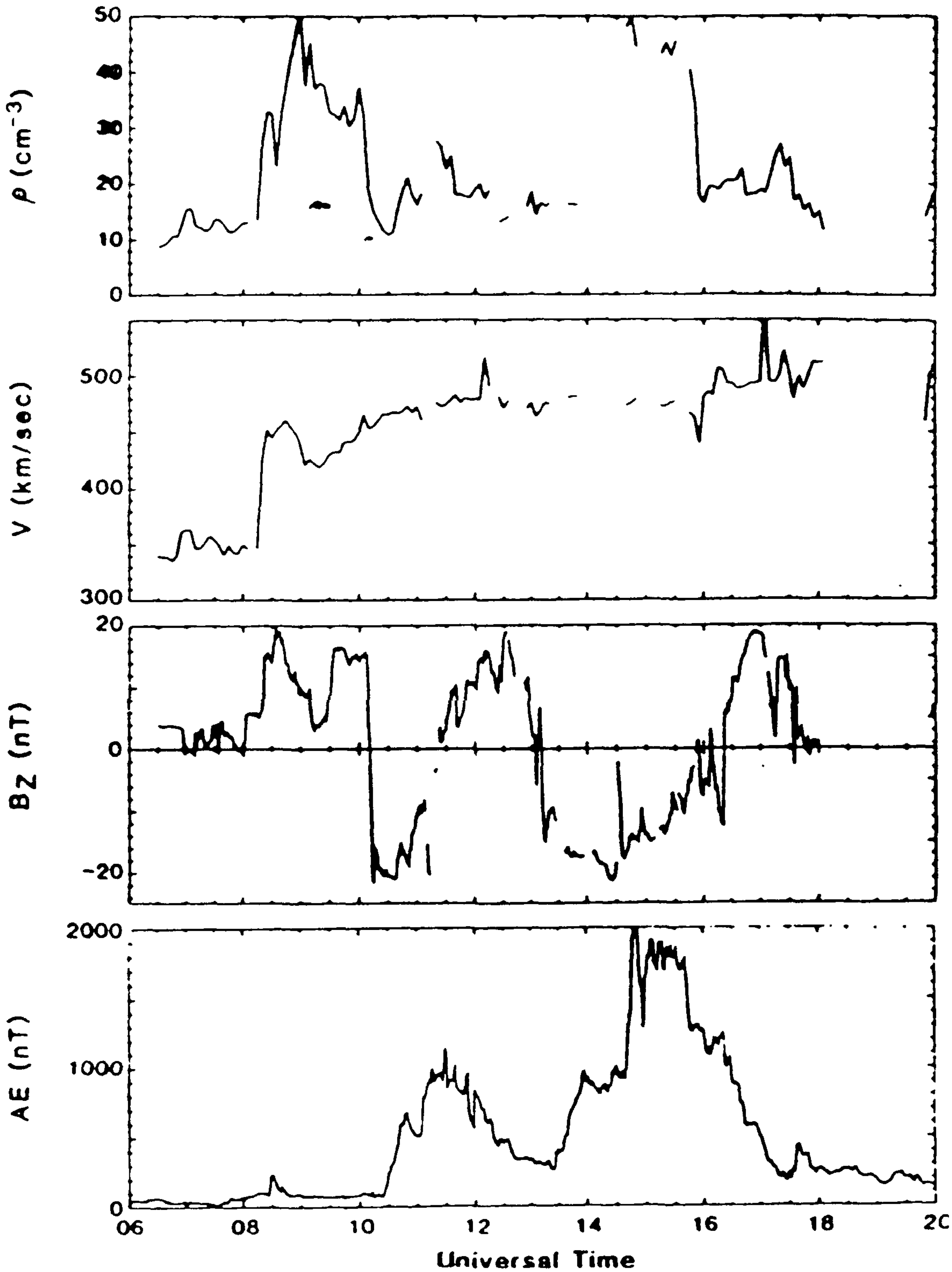
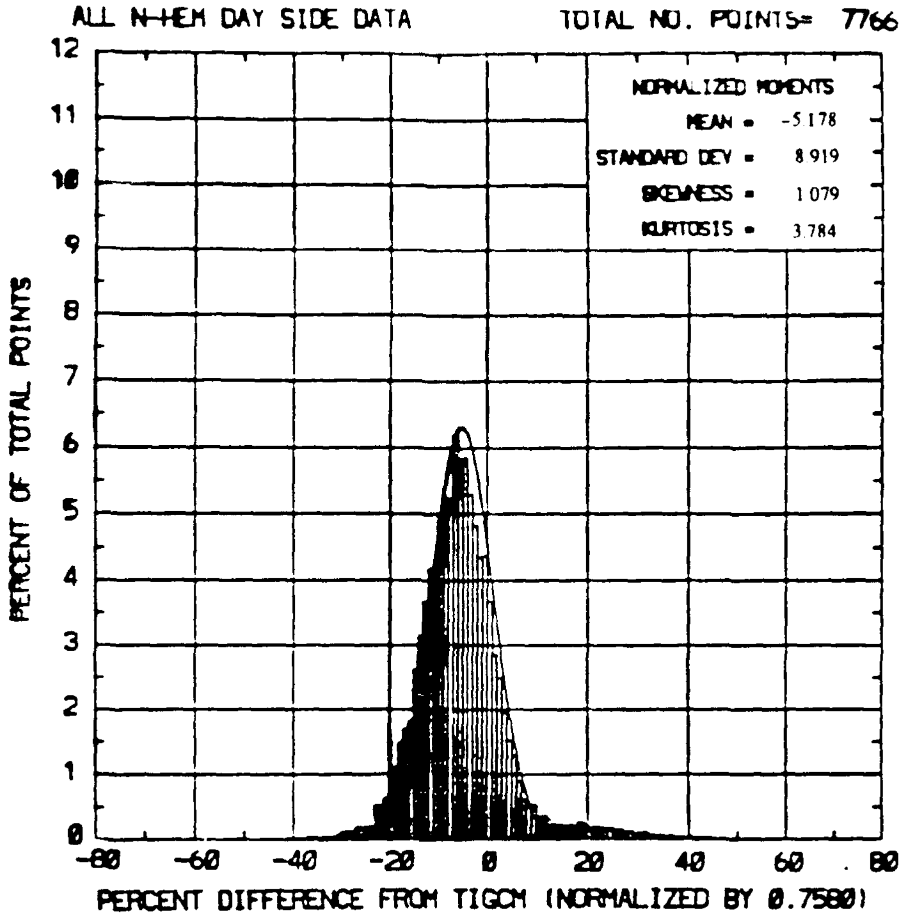

50
40
30
20
10
0
ρ (cm⁻³)
500
400
300
V (km/sec)
20
0
-20
Bz (nT)
2000
1000
0
AE (nT)
06
08
10
12
14
16
18
20
Universal Time

Fig. 19


ALL N-HEM DAY SIDE DATA
TOTAL NO. POINTS= 7766
NORMALIZED MOMENTS
MEAN = -5.178
STANDARD DEV = 8.919
SKEWNESS = 1.079
KURTOSIS = 3.784
PERCENT OF TOTAL POINTS
PERCENT DIFFERENCE FROM TIGCM (NORMALIZED BY 0.7580)

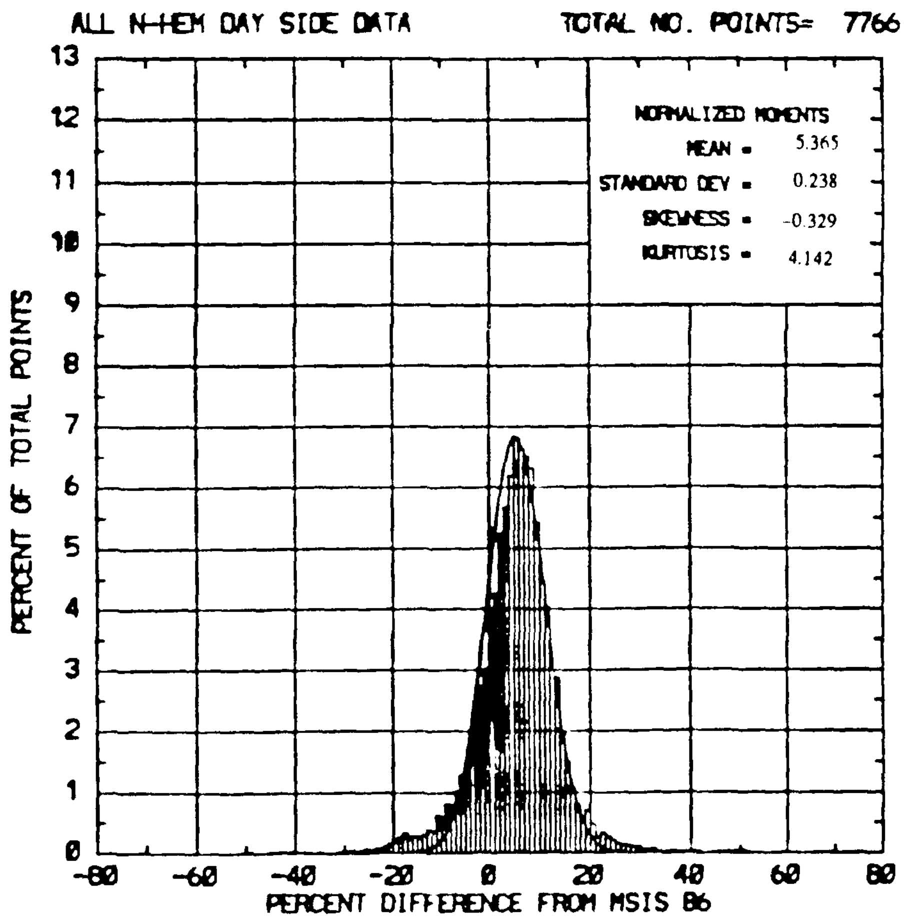
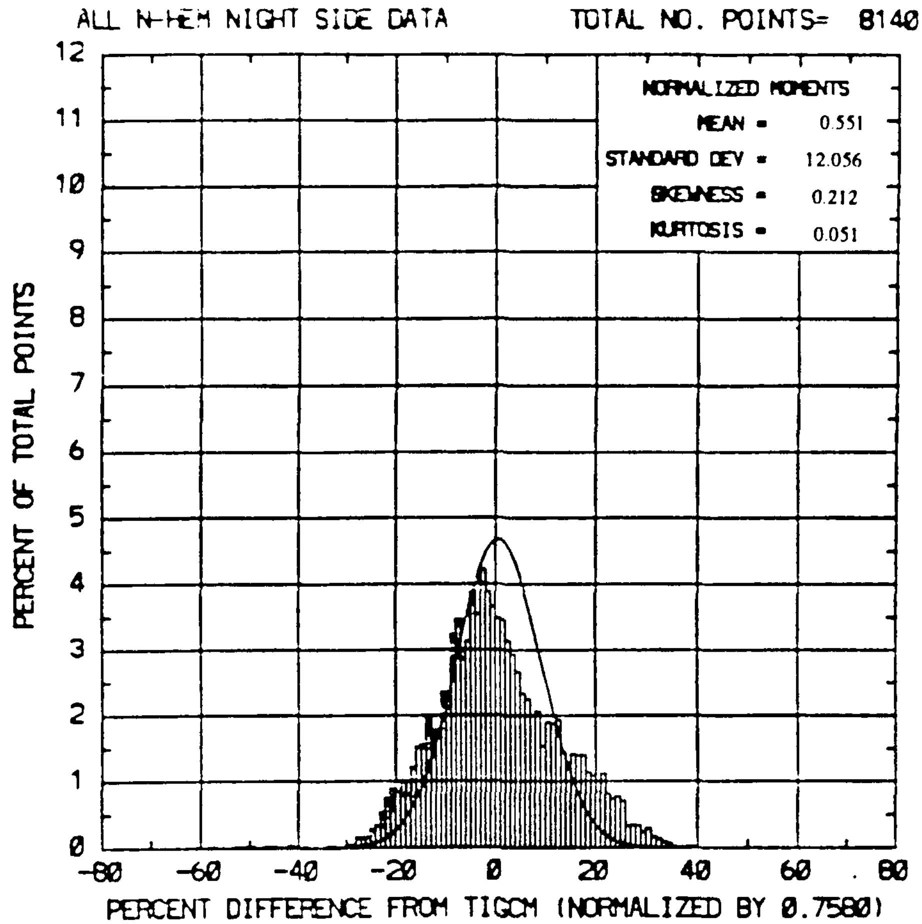

ALL N-HEM DAY SIDE DATA
TOTAL NO. POINTS= 7766
NORMALIZED MOMENTS
MEAN = 5.365
STANDARD DEV = 0.238
SKEWNESS = -0.329
KURTOSIS = 4.142
PERCENT OF TOTAL POINTS
PERCENT DIFFERENCE FROM MSIS 86

Fig. 20


ALL N-HEM NIGHT SIDE DATA
TOTAL NO. POINTS= 8140
NORMALIZED MOMENTS
MEAN = 0.551
STANDARD DEV = 12.056
SKEWNESS = 0.212
KURTOSIS = 0.051
PERCENT OF TOTAL POINTS
PERCENT DIFFERENCE FROM TIGCM (NORMALIZED BY 0.7580)

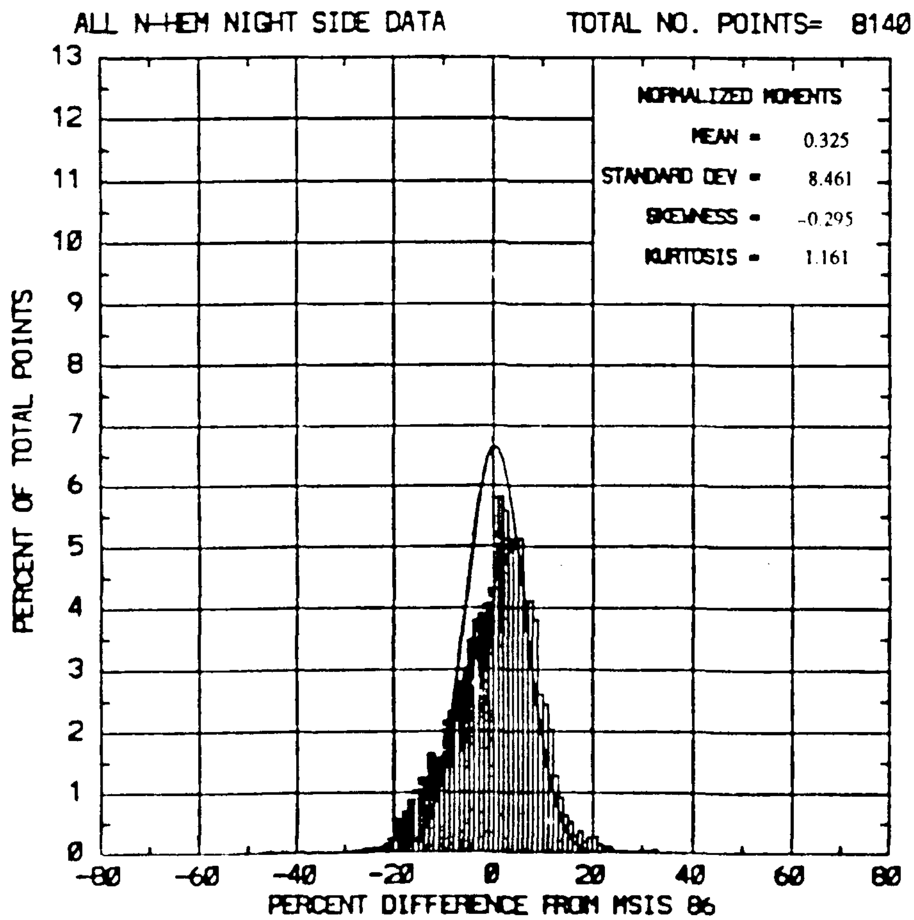

ALL N-HEM NIGHT SIDE DATA
TOTAL NO. POINTS= 8140
NORMALIZED MOMENTS
MEAN = 0.325
STANDARD DEV = 8.461
SKEWNESS = -0.295
KURTOSIS = 1.161
PERCENT OF TOTAL POINTS
PERCENT DIFFERENCE FROM MSIS 86

Fig. 21

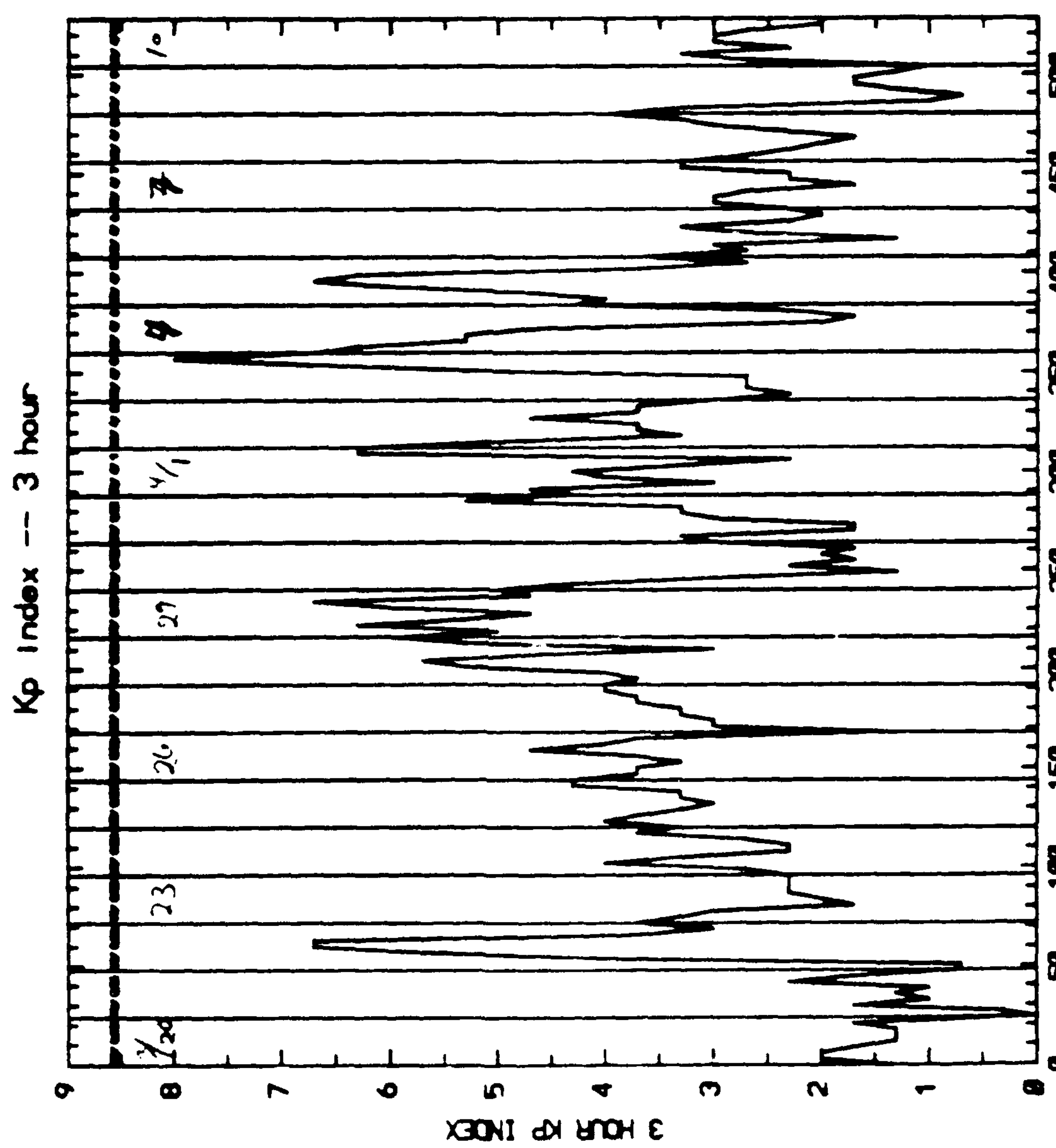


Fig. 22

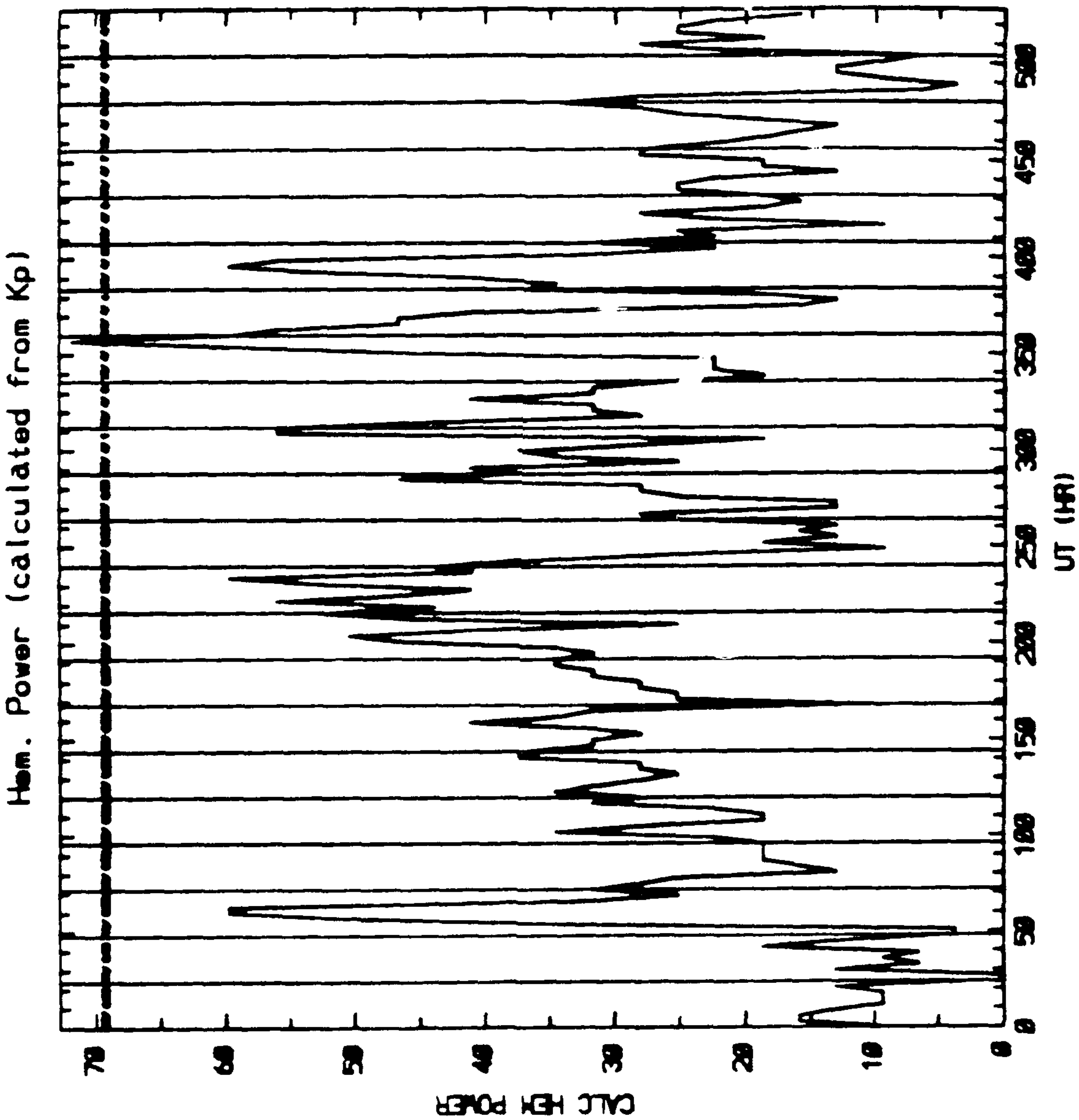
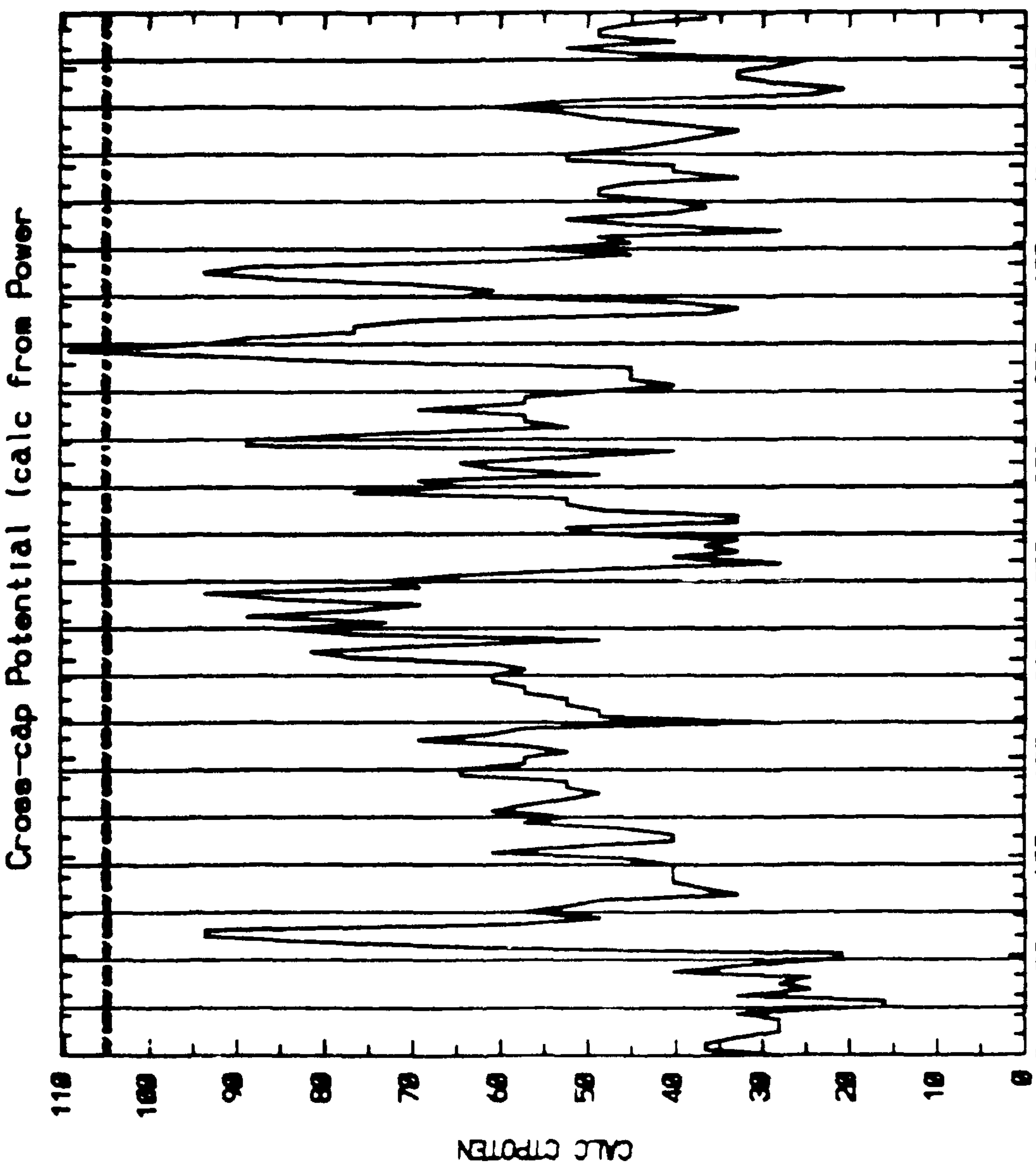
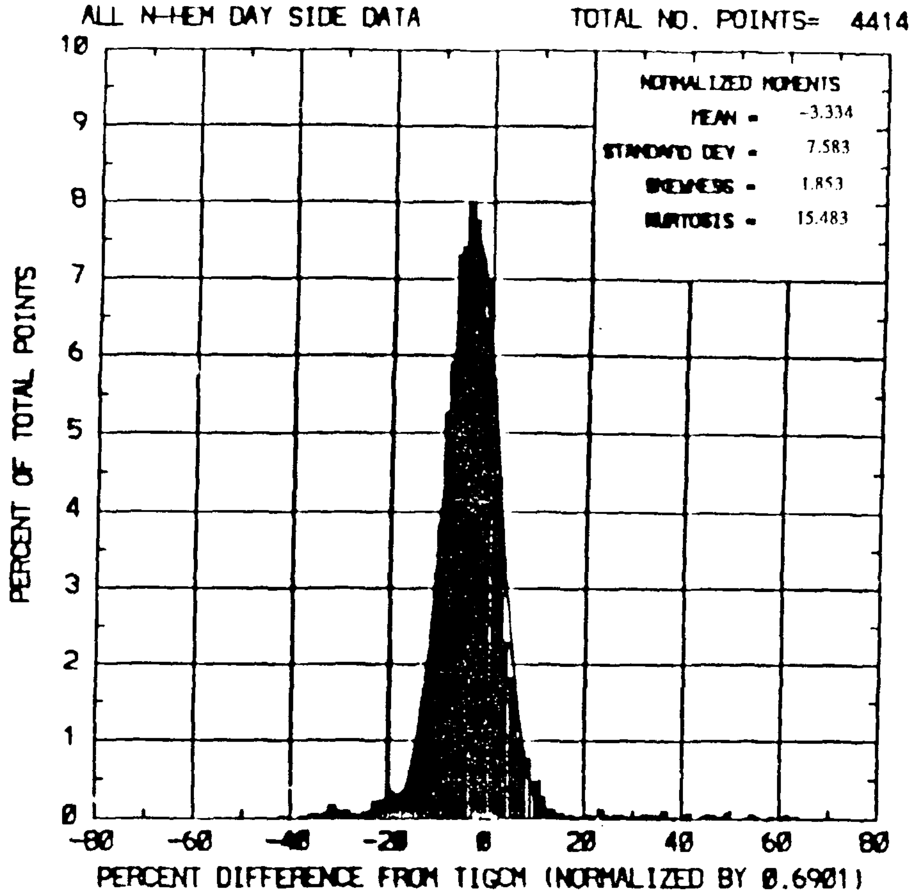

Hem. Power (calculated from Kp)
UT (HR)
CALC HEM POWER
0
50
100
150
200
250
300
350
400
450
500
10
20
30
40
50
60
70

Fig. 23



Cross-cap Potential (calc from Power
UT (HR)
CALC CTPOTEN
0
50
100
150
200
250
300
350
400
450
500
10
20
30
40
50
60
70
80
90
100
110

Fig. 24


ALL N-HEM DAY SIDE DATA
TOTAL NO. POINTS= 4414
NORMALIZED MOMENTS
MEAN = -3.334
STANDARD DEV = 7.583
SKEWNESS = 1.853
KURTOSIS = 15.483
PERCENT OF TOTAL POINTS
PERCENT DIFFERENCE FROM TIGCM (NORMALIZED BY 0.6901)

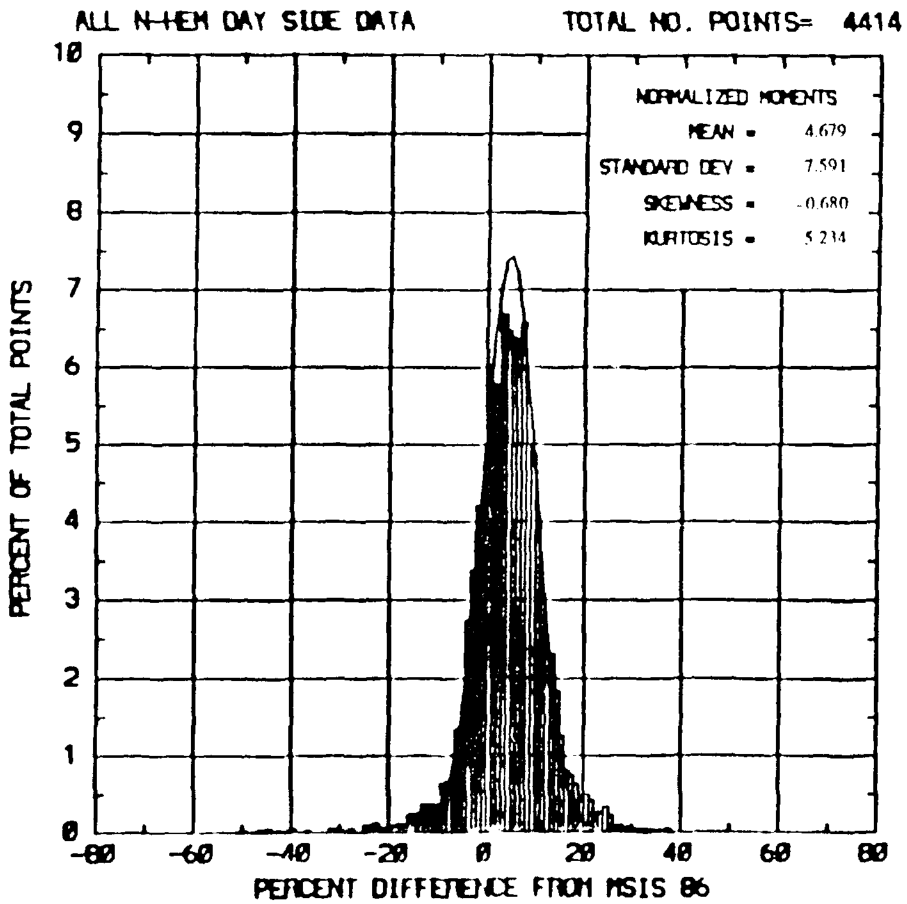
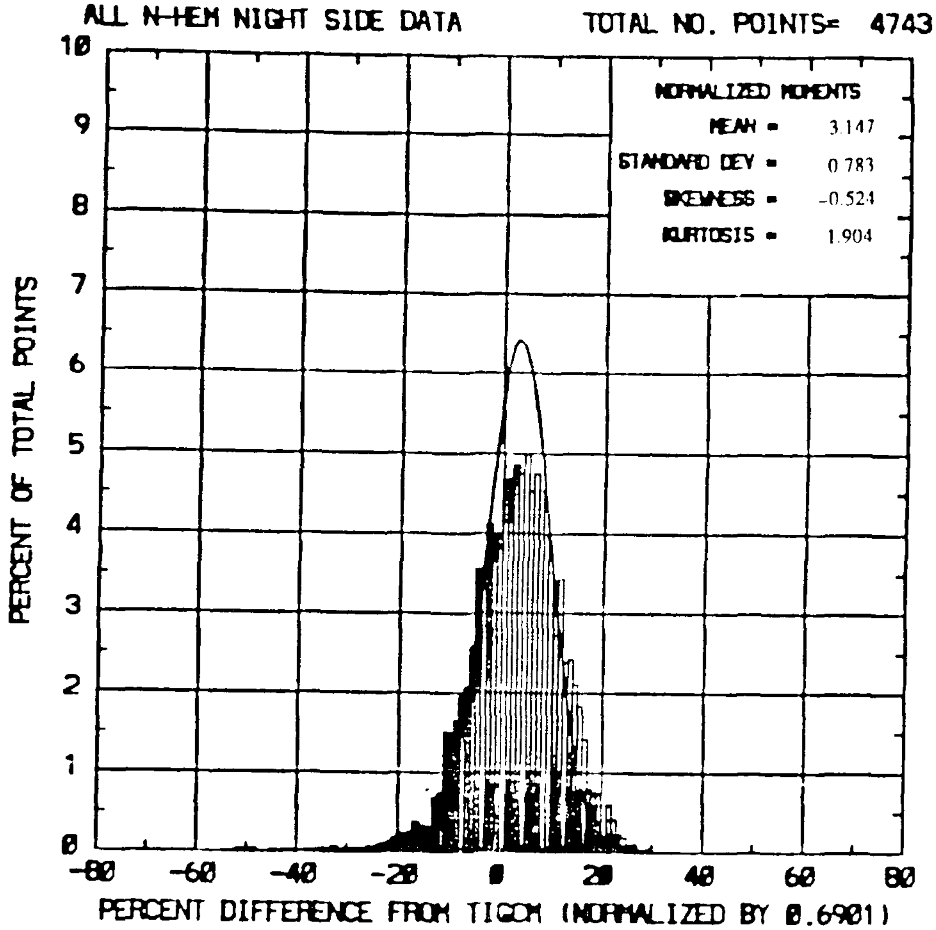
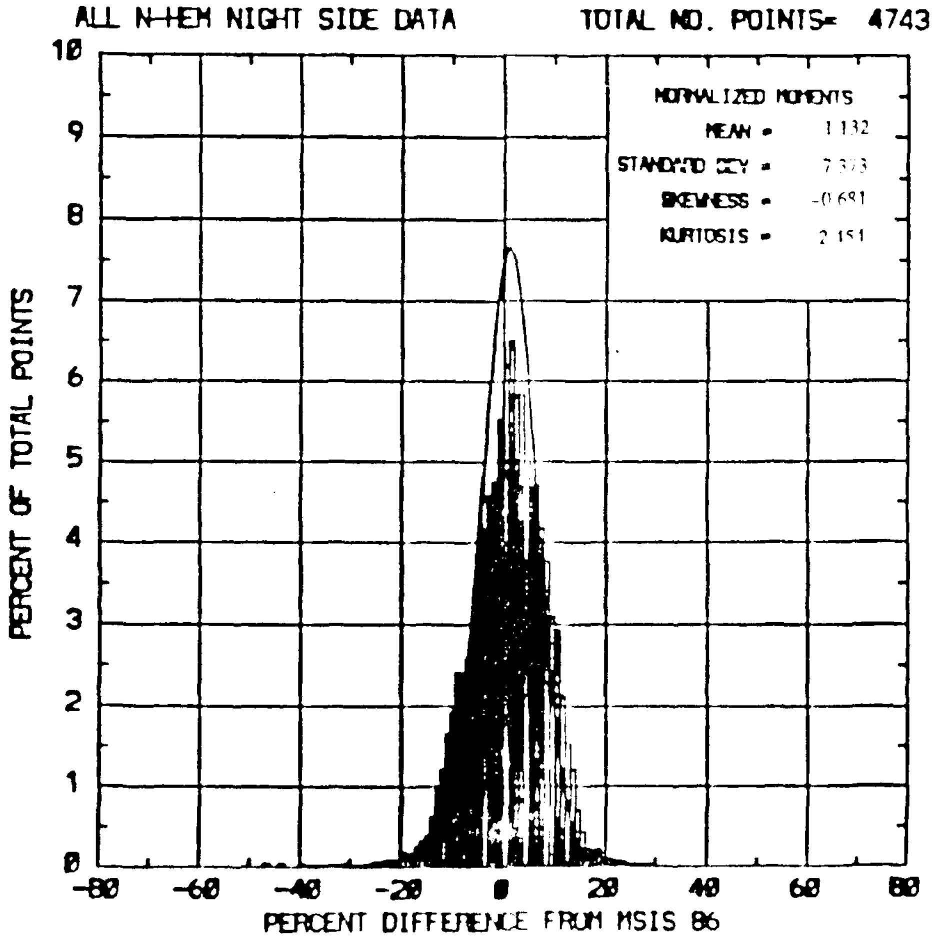

ALL N-HEM DAY SIDE DATA
TOTAL NO. POINTS= 4414
NORMALIZED MOMENTS
MEAN = 4.679
STANDARD DEV = 7.591
SKEWNESS = -0.680
KURTOSIS = 5.234
PERCENT OF TOTAL POINTS
PERCENT DIFFERENCE FROM MSIS 86

Fig. 25



ALL N-HEM NIGHT SIDE DATA
TOTAL NO. POINTS= 4743
NORMALIZED MOMENTS
MEAN = 3.147
STANDARD DEV = 0.783
SKEWNESS = -0.524
KURTOSIS = 1.904
PERCENT OF TOTAL POINTS
PERCENT DIFFERENCE FROM TIGCM (NORMALIZED BY 0.6901)



ALL N-HEM NIGHT SIDE DATA
TOTAL NO. POINTS= 4743
NORMALIZED MOMENTS
MEAN = 1.132
STANDARD DEV =
SKEWNESS = -0.681
KURTOSIS = 2.151
PERCENT OF TOTAL POINTS
PERCENT DIFFERENCE FROM MSIS 86

Fig. 26

SUMMARY AND CONCLUSIONS

- TIGCM used to simulate time-dependent variations from 20 March to 29 March 1979.
- Auroral particle precipitation specified by Hemisphere Power Index.
- Ionospheric convection pattern variations prescribed by solar wind variations.
- Results show considerable variability in all TIGCM fields in response to high latitude forcings, e.g., latitudinal surges and recovery.
- Test of aeronomic scheme stability and ability to relax to pre-storm conditions.
- Need to develop post processors for analysis of physical, chemical and radiative processes, e.g., wave energy, energy of mean flow, energy radiated etc.

SUMMARY AND CONCLUSIONS

- TIGCM compares reasonably well with overall variations predicted by MSIS-86, but with considerably more structure and variability.

- Compared SETA-1 measured density with MSIS-86 and TIGCM predictions along satellite path for the 9 day period:
  - TIGCM and MSIS-86 give comparable agreement with dayside measurements.
  - MSIS-86 performs better at night than TIGCM.

- Need to improve plasma exchange processes between magnetosphere and ionosphere at night to prevent F-region decay.

- TIGCM parameterized inputs appear to be too large at times and especially in later phase of storm period.

- Need to continue comparison studies for different periods using DE data, AE data and data from CEDAR campaigns.

TABLE 2

	Solar Minimum (76200)		Solar Maximum (79050)	
No.	λ (S_{min})	ΔT (S_{min})	λ (S_{max})	ΔT (S_{max})
1	303.78	53.5	303.78	92.0
2	850–900	20.3	850–900	51.7
3	150–200	19.4	150–200	47.6
4	584.33	15.1	300–350	43.9
5	900–950	14.2	584.33	41.7
6	629.73	12.2	900–950	34.5
7	200–250	9.9	200–250	33.6
8	250–300	8.3	250–300	30.0
9	300–350	8.1	303.31	21.6
10	554.37	8.1	629.73	20.2
11	800–850	7.7	284.15	20.1
12	368.07	7.2	800–850	17.0
13	950–1000	6.6	350–4000	16.6
14	750–800	5.5	554.37	13.8
15	500–550	5.4	450–500	13.7
16	789.36	4.5	500–550	13.1
17	550–600	4.3	950–1000	13.1
18	400–450	4.2	750–800	11.4
19	609.76	4.1	368.07	10.5
20	703.31	3.6	609.76	9.9
21	450–500	3.5	400–450	7.6
22	256.3	3.3	789.36	7.5
23	303.31	2.8	550–600	7.3
24	350–400	2.6	256.3	5.8
25	650–700	2.4	703.31	5.0
26	465.22	2.4	977.02	3.7
27	770.41	2.1	770.41	3.4
28	600–650	2.1	600–650	3.4
29	765.15	2.0	650–700	3.3
30	977.02	1.96	100–150	3.3
31	700–750	1.90	250–300	3.2
32	100–150	1.81	700–750	3.0
33	284.15	1.66	50–100	2.9
34	1031.91	0.77	765.15	2.8
35	1000–1050	0.57	1031.91	0.48
36	50–100	0.33	1000–1050	0.29
37	1025.72	0.11	1025.72	0.12

SR only T_∞ = 442 K   SR only T_∞ = 473 K

SR + EUV T_∞ = 746 K   SR + EUV T_∞ = 1250 K

THE TIGCM ON THE NCAR CRAY XMP-48

PROGRAM REQUIREMENTS:

PROGRAM LENGTH IN CORE:	.78 megawords
DISC REQUIREMENTS:	
Starting history volume (released after reading)	$\leq$ 20 megawords
Input dataset (released after reading)	0.48 megawords
History volume (written during course of model run)	$\leq$ 20 megawords (up to 13 histories)
Copy of history volume (for disposal to mass store and save on disks)	$\leq$ 20 megawords
TOTAL DISK REQUIREMENTS:	60.48 megawords
SSD (OR DISKS) REQUIREMENTS:	
Current and Updated Copies of Model Fields 2 x 1576317 =	3.2 megawords
Copy of Input Data Set	.41 megawords
These data sets are used during time stepping and employ optimized unblocked data flow.	
TOTAL SSD NEEDS:	3.6 megawords

- Model requires 1722 seconds of CPU time to simulate one day using a 5 minute time step and writing histories every hour.
- If a 4 minute time step is needed, the time for a day's simulation increases to 2152 secs.
- The model is vectorized and runs at 117 megaflops/second when time stepping.
- A value of 50 megaflops/second is considered to be reasonably efficient.
- The code does not make use of multiprocessing.

3.0 Quarterly Status Report #3: 1 November 1989 - 31 December 1989

THE UNIVERSITY OF MICHIGAN

SPACE PHYSICS RESEARCH LABORATORY

Quarterly Status Report #3
Covering the Period 1 November 1989 through 31 December 1989
University of Michigan Account 080063

DEVELOPMENT OF A VECTOR SPHERICAL HARMONIC (VSH) MODEL OF THE NEUTRAL THERMOSPHERE

by

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AFGL Contract F19628-89-K-0026

Prepared for:

Air Force Geophysics Laboratory
Air Force Systems Command
L.G. Hanscom Air Force Base
Bedford, Massachusetts 01731

ATTN: Dr. Frank Marcos

Executive Summary.

The Air Force has requirements for accurate knowledge and specification of the state variables of the Earth's thermosphere. Work done under this contract will lead to a new model of global thermospheric density that can be used to specify and forecast neutral densities, temperatures, and winds for a wide range of solar and geomagnetic activity. The model will be based on simulations made with the National Center for Atmospheric Research (NCAR) Thermospheric/Ionospheric General Circulation Model (TIGCM) and on data. The model will be capable of using real-time geophysical indices or data from ground-based and satellite inputs and will provide neutral variables at specified locations and times in the altitude range 90 - 1500 km. The model will be semi-empirical and will be based on a new Vector Spherical Harmonic (VSH) analysis technique developed at the University of Michigan that permits the incorporation of the TIGCM outputs into the model. The VSH model will be provided for use by the Air Force in an operational setting as a more accurate version of existing models of the neutral upper atmosphere.

During the past reporting period, the effort at the University of Michigan has focused on the further development and improvement of the VSH model and the design and implementation of an objective analysis scheme for the incorporation of density measurements. In addition, a research and development science team has been established at the University of Michigan to aid Prof. Killeen in the administration and implementation of the model development effort. This team, comprising Prof. Killeen, Drs. Johnson, and Burns and Mr. Raskin, meets on a regular weekly basis.

Prior to the last reporting period, a preliminary version of the VSH model was sent to GL for evaluation, complete with 12 sets of coefficients, documentation and source code. An initial response from DOAS (Capt Osedacz) was subsequently received (dated 10 October 1989) with helpful comments. These comments from the end user of the model have been considered and the suggested work related to additional documentation and code modifications has been carried out during the past reporting period. A preliminary version of the objective analysis scheme for the ingestion of density data has been developed and tested, using density measurements from the SETA instrument as a first test case. Work has also been carried out to refine the operational aspects of the model (i.e. structured code development, documentation, flags and inputs, data ingestion module, coefficient modification module, etc.).

Detailed sensitivity and model validation studies using the TIGCM have also been carried out during the past reporting period. The relevant sensitivities of the recovered densities to variations in the different model inputs have been quantified. The TIGCM for the Phase 1 Model has been frozen and a significant number (18) model runs, corresponding to different geophysical conditions, have been performed and incorporated into the VSH library.

Scientists from the University of Michigan and from NCAR attended the second quarterly review meeting in Boulder on 21 September 1989. This meeting was also attended by many other scientists from various institutions as well as Air Force Personnel.

Plans for the upcoming reporting period include the further development of the VSH approach, leading to delivery of the Phase 1 Model at the end of FY 1990. Additional key validation and model improvement efforts will be carried out at NCAR. Further TIGCM runs will be made and continuing model validation tests on these runs will be carried out. An improved treatment for the description of the output fields in the vertical dimension will be designed and implemented. A theoretical model for neutral exospheric hydrogen will be chosen and initial efforts undertaken to incorporate it into the VSH. A scheme for the use of the MSIS model within the VSH framework will be designed. MSIS predictions are useful to extend the TIGCM calculation beyond the model boundaries and to assist in normalization for total densities in the absence of experimental data. A second, updated (but still preliminary) version of the VSH model will be delivered to GL for further evaluation. Lastly, a significant effort to coordinate the activities of the neutral and ionospheric modeling groups will be made during the upcoming period.

3.1 Progress during the current reporting period

Progress prior to the current reporting period was presented at the second quarterly meeting in Boulder, Colorado on September 21 1989. Progress during the current reporting period was be presented at the third quarterly review meeting in Colorado Springs on January 30, 1990. The detailed agenda for this meeting is shown in Appendix 3.1. Presentations were made by Prof. Killeen, Drs. Johnson and Burns, and Mr. Raskir of the Unviersity of Michigan and Dr. Roble of NCAR. Materials from their presentations are included as appendicies to this report.

Project personnel and their responsibilities are shown in Appendix 3.1. Appendix 3.2 reviews project milestones through the 5-year contract and summarizes the current status of the project. In spite of a late start for the first fiscal year of the contract in March, 1989, progress in model development is on schedule. Tasks 1 through 3 have been completed and the science team is currently continuing work on tasks 4 through 7 to achieve an on time delievery of the Phase 1 Model at the end of the second fiscal year.

The status of the model and plans for its further development and refinement are presented in Appendix 3.3. A plan for data flow and manipulation within the VSH model has been established, including the capability for modification of both coefficient files and VSH output fields. Default density models (MSIS, exospheric H) will be utilized at altitudes outside the range of TIGCM validity.

Total neutral density, which is calculated from the mass mixing ratios, has been added as an output field. We are currently considering adding an additional set of coefficients for the total density to the coefficient files to expedite potential objective analysis schemes.

The mathematical formulation for the several transformations utilized in the VSH model are specified in Appendix 3.3. Alternatives to the Fourier time representation, such as Chebyshev polynomials, are currently being considered for application to temporally variable storm-time conditions. In order to adequately describe high latitude and low altitude fields, we are also investigating alternatives to the spatial transform currently implemented. As more altitudes are retained from the TIGCM, mathematical representations for the vertical variation of the coefficient fields must be developed. We are currently investigating potential formulations.

An output field modifier has been developed for the mass density. We also plan to develop an operational coefficient modification module (currently coefficient files can only be modified on the NCAR Cray).

Our responses to the 10 October 1989 memo from Capt. Osedacz are indicated in Appendix 3.3. Specifically, we have completed the addition of mass density as an output field. We have provided coefficient files in ASCII format, and additionally provided a conversion program back to binary. All library subroutines have been documented internally, and the units of all output variables have been specified. We are in the process of developing a technical manual for the VSH model.

The status of NCAR TIGCM runs and coefficient file production for Phase 1 Model development is summarized in Appendix 3.4. Presently 18 TIGCM Phase 1 runs have been completed for solar minimum and maximum conditions, three levels of geomagnetic activity, and solstices and equinox. To date, eleven of the corresponding coefficient files have been generated.

The objective analysis schemes utilized in the VSH model are reviewed in Appendix 3.5. The objective analysis scheme for neutral wind data (Dynamics Explorer measurements) was developed in the last reporting period. This period, we have developed a preliminary objective analysis technique for ingesting total density measurements. In this scheme, only the variation of density with altitude is considered, and the VSH output fields are adjusted to match the measured altitude profile. We are currently using linear fits to the measured and model profiles in this transformation. Two examples of the capability of this technique are shown in Appendix 3.5.

Potential improvements to this preliminary scheme include the utilization of more appropriate functions, such as quadratic or higher order forms. These will certainly become necessary as the altitude range of the available data increases. Additionally, an option to modify coefficient files directly will provide computational efficiency. A default to TIGCM adjusted to match MSIS absolute density at low altitude and to MSIS augmented by exospheric H above the maximum TIGCM altitude will also be necessary. Techniques for density field modification including latitudinal, longitudinal, and universal time dependences need to be developed. Finally, the region of influence for perturbations on average profiles will need to be considered.

TIGCM developments and the results of the Task 3 sensitivity study are summarized in Appendix 3.6. There has been considerable progress in the specification of physical processes in the TIGCM. Among other improvements, viscous heating and O+ plasma exchange have been added, the tidal specification has been improved, and altitude dependent gravity has been added. Sensitivity studies for several variables have been performed which show the relative change in TIGCM temperature and density to 10% changes in solar EUV and SRC, ± 10 nT changes in By, ± 10 kV changes in potential drop, and changes in the lower boundary tidal specification.

3.2 Plans for the next reporting period.

Plans for the next quarter of effort relate to the work statement given in Appendix 3.2. Specifically, work on tasks 4-7 will continue. Major action items for the next 3 months are indicated in Appendix 3.7. These include incorporation of an exospheric hydrogen model above 500 km, an MSIS default scheme, and continued development and implementation of the library scheme for Phase 1 Model delivery. We will also deliever a second preliminary test version of the VSH to the Space Forecast Center for continuing evaluation, and develop further coordination of efforts with the ionospheric modelling group. Continuing work on Tasks 4 through 7 will include further development and refinement of the VSH algorithm, specifically the vertial and storm time representations to be utilized. Refinement and development of field and coefficient modifiers will continue. The TIGCM sensitivity study will also continue, as will Phase 1 TIGCM runs for model delievery at the end of FY 1990.

Appendix 3.1

Agenda

VSH Model Review
Colorado Springs
30 Jan 1990

1. Introduction	F. Marcos	GL	0830
2. Contractor Personnel & Responsibilities	T. Killeen	U of M	0900
3. Schedule & Milestones	R. Johnson	U of M	0915
4. Current Status of Model	R. Raskin	U of M	0940
5. TIGCM Run Status & Coefficient Files	A. Burns	U of M	1015
Break			
6. Objective Analysis	R. Johnson	U of M	1050
7. TIGCM Model Progress and Sensitivity Study	R. Roble	NCAR	1110
8. Contract Action Items	T. Killeen	U of M	1200
9. Space Command Operational Requirements and Model Review	R. Osedacz	DOJ	1215
10. Concluding Remarks	F. Marcos	GL	1230
11. Adjourn			1240

VSH Model Development Schedule

Summary of Current Status - Contacts at U of M

Prof. Killeen	Overall Project Direction, Theoretical Development of VSH technique and Objective Analysis	(313) 747-3435
Dr. Johnson	Project Coordination and requirements, Density Objective Analysis, Validation Studies	(313)747-3430
Dr. Burns	TIGCM run coordination and status of coefficient file library	(313)747-3445
Mr. Raskin	Software Development	(313)763-6214

VSH Model Development Schedule

Summary of Current Status - Contacts at NCAR

Dr. Roble	TIGCM Development and Finalization, Validation and Sensitivity Studies	(303) 497-1562
Mr. Foster	Graphical Displays, Networking	(303) 497-1595

Appendix 3.2

Review of Schedule and Milestones

- 13 Programmatic Tasks identified in Statement of Work
- Years refer to Fiscal Years, starting in FY 1989 - Late start 3/89
- Progress on schedule

Task Initiation/Completion Guidelines

Fiscal Year	Initiate Tasks	Complete Task(s)
1989	1,2,3,4,5	1
1990	6,7	2,3,4,5
1991	8,9,10	6,7,8,9
1992	11	10,11
1993	12,13	12,13

VSH Model Development Schedule

Year 1.

- Task 1: Program Definition:
  U of M and NCAR to develop a detailed program schedule for the 5-year effort - present major program milestones in the first semi-annual report
- Task 2: TIGCM Verification:
  Verify new model with satellite, rocket, and ground-based predictions
- Task 3: Finalize development of new TIGCM for the VSH Phase I
- Task 4: Develop algorithms for the VSH. Vector Spherical Harmonic Expansion and Objective Analysis
- Task 5: Sensitivity study of the aeronomic scheme used in the TIGCM Impacts of uncertainties in rate coefficients, solar EUV, F107 fluxes, auroral inputs.

VSH Model Development Schedule

Year 2.

- Report on Task 1
- Complete and Report on Tasks 2-5
- Start Task 6: Perform TIGCM runs to provide data base for use in the Phase I (250 - 1500 km) operational model
- Start Task 7: Merger of VSH with MSIS and available experimental data. Extend VSH beolw 250 km using MSIS. Develop objective analysis scheme to incorporate experimental data based on existing optimal estimator algorithms. Incorporate DE, and SETA data sets
- Delivery of VSH (mk I) at end of Fiscal Year (250 - 1500 km)

VSH Model Development Schedule

Year 3.

- Complete and Report on Tasks 6-7
- Start and finish Task 8:
  Perform TIGCM runs to generate data for Phase II VSH (includes 140 - 250 km region). Validation and test case studies
- Start and finish Task 9: Develop VSH algorithms to represent thermospheric properties in 140- 250 km region
- Start Task 10: Perform TIGCM runs for the Phase III VSH (includes 90 - 1500 km range). Validation and test studies
- Report on Tasks 8-9
- Delivery of VSH (mk II) at end of Fiscal Year (140 - 1500 km)

VSH Model Development Schedule

Year 4.

- Start and finish Task 10: Update VSH with TIGCM runs for 90-140 km region and incorporate any new data sets (ADS spacecraft?)
- Start and finish Task 11: Feasibility of operational TIGCM. Work will begin on adapting an operational and validated TIGCM for use on Air Force computer system
- Report on Tasks 10-11
- Delivery of VSH (mk III) at end of Fiscal Year (90 - 1500 km)

VSH Model Development Schedule

Year 5.

- Task 12: Deliver Operational TIGCM
- Task 13: Continued validation and experimental data ingestion. Maintenance of VSH
- Report on Tasks 12 and 13

Model Development Progress

● - Milestone Completed ◗ - Work in Progress ○ - Work not yet begun

Task	Subtask	Resp. Org.	FY89 M	FY89 AMJ	FY89 JAS	FY90 OND	FY90 JFM	FY90 AMJ	FY90 JAS	FY91 OND	FY91 JFM	FY91 AMJ	FY91 JAS	FY92 OND	FY92 JFM	FY92 AMJ	FY92 JAS	FY93 OND	FY93 JFM	FY93 AMJ	FY93 JAS	FY94 OND
1	Program Definition	Mich/NCAR	(late start) ●																			
2	TIGCM Verification				●																	
3	TIGCM Frozen	NCAR			●																	
4	VSH Technique Defn Library Approach TIGCM Input Strategy	Mich Mich NCAR/Mich			◗ ◗ ◗																	
5	Sensitivity Defn. of # of runs	NCAR/Mich NCAR/Mich				◗	 ◗															
6	TIGCM Phase 1 runs	NCAR							◗													
7	TIGCM/Exp. Merger DE data, SETA data Delivery Mark 1 VSH	Mich Mich Mich/NCAR							◗ ◗ ○													
8	TIGCM Phase 2 runs Verification above 140 km	NCAR/Mich NCAR/Mich									○	 ○										
9	Delivery Mark 2 VSH Verification of VSH	Mich/NCAR Mich/NCAR											○ ○									
10	Delivery Mark 3 VSH Verification of VSH	Mich/NCAR Mich/NCAR															○ ○					
11	Feasibility of operational TIGCM	Mich/NCAR															○					
12	Deliver operational TIGCM	Mich/NCAR																			○	
13	Final Validation and Final Model Improvements	Mich/NCAR																				○
	QUARTERLIES		~	●	●	◗	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

VSH Model Development Schedule

Summary of Current Status - Background

- Late start - March 27 1989 start date
- U of M subcontract to NCAR
- Personnel at U of M: Division of Responsibilities
  - Prof. Killeen: Project Director
  - Dr. Johnson: Project Coordinator - Density Objective analysis, TIGCM Validation studies, Ground-based data ingestion
  - Dr. Alan Burns: TIGCM and VSH Coefficient File Coordinator, TIGCM Validation studies
  - Mr. Rob Raskin: Programmer, VSH library approach
- Personnel at NCAR: division of responsibilities
  - Dr. Roble: Finalization of TIGCM for VSH versions, TIGCM Validation and sensitivity studies
  - Mr. Ben Foster: Graphical displays, networking

VSH Model Development Schedule

Summary of Current Status - Detail

Task 1 - Program Definition: <u>Completed</u> as reported in 2nd Quarterly Report

Task 2 - TIGCM Verification: <u>Completed</u>. Verification progress using SETA data reported at 2nd Quarterly by Dr. Roble

Task 3 - TIGCM Frozen: <u>Completed</u> following results of Task 2 validation study (Dr. Roble)

VSH Model Development Schedule

Summary of Current Status - Detail Continued

Task 4 - VSH Algorithm Development: Continuing. (Mr. Raskin, Dr. Johnson)

- VSH technique for neutral model application in process of definition and implementation
- Alternatives to Fourier time representation for storm events under consideration
- Techniques for satellite and ground-based data ingestion are currently being developed and refined.
- Design of library approach in process of development and implementation.

Task 5 - TIGCM Sensitivity Study: Continuing. Reported here by Dr. Roble. Results will be used to refine number of TIGCM runs required.

VSH Model Development Schedule

Summary of Current Status - Detail Continued

Task 6 - TIGCM Phase 1 Runs: Continuing. (Dr. Burns, Dr. Roble)

- Design of overall model run strategy developed as reported in 2nd Quarterly.
- 18 TIGCM runs completed for:
  - equinox and the solstices
  - 3 levels of geomagnetic activity
  - solar cycle minimum and maximum

Task 7 - Merger of VSH, MSIS and available data: Continuing.

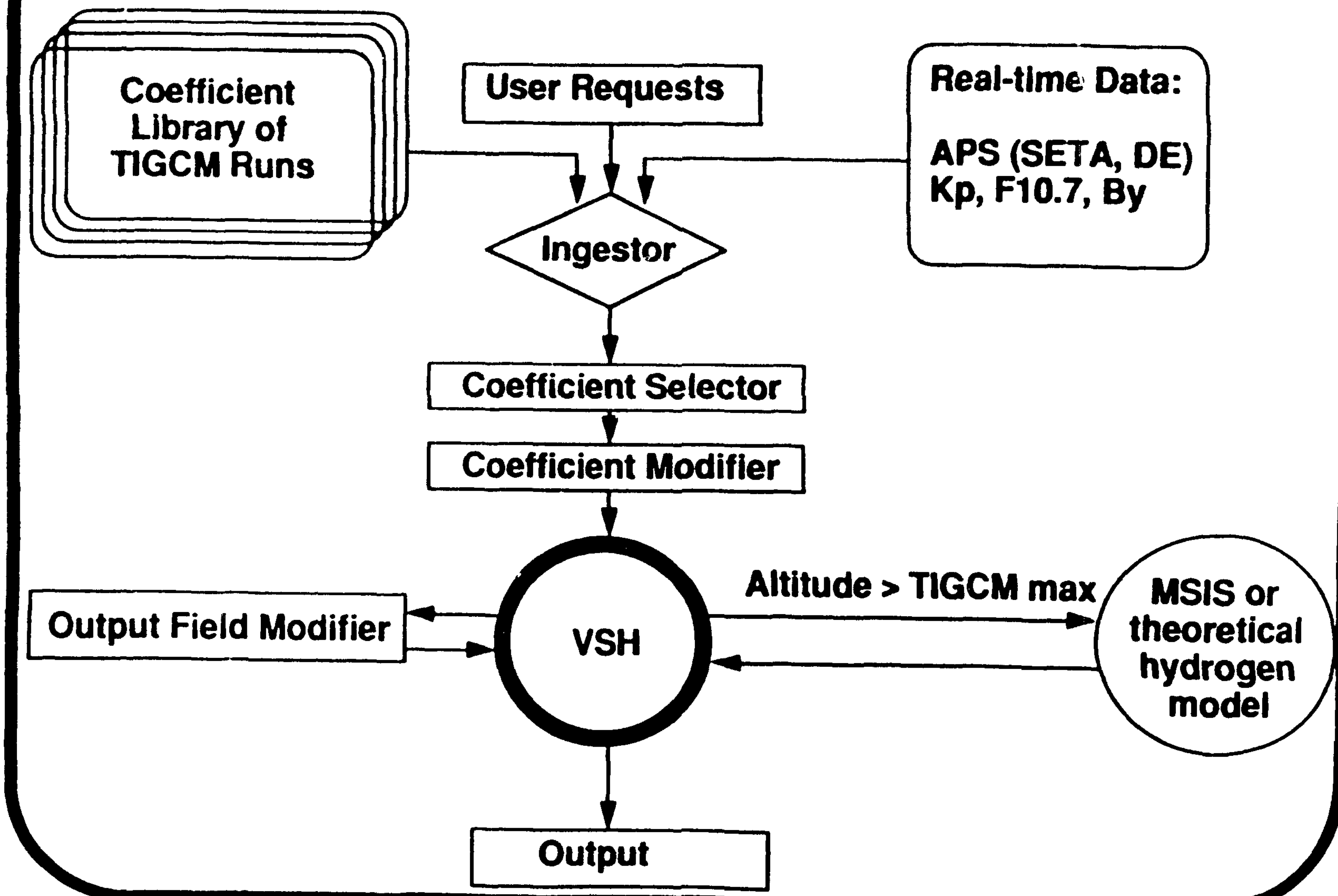
- Algorithms currently being developed to merge with TIGCM adjusted to match MSIS absolute density at low altitude and ingest available data sets (SETA, DE) (Dr. Johnson, Mr. Raskin)
- Mark 1 VSH to be delivered end of FY 90.

VSH Model Development Action Items

- Task 4: Continue VSH algorithm development, including vertical representation, field and coefficient modifiers, representation of temporal variations (storms)
- Task 5: Continue TIGCM Sensitivity Study
- Task 6: Continue Phase I TIGCM runs
- Task 7: Continue development and refinement of objective analysis schemes; complete implementation of model front-end, coefficient selector, MSIS default, exospheric H model

Appendix 3.3

VSH DATA FLOW DIAGRAM



USER REQUESTS

User specifies:

- Time (UT)
- Longitude
- Colatitude
- Altitude (km) or one of three pressure surfaces (E, F1, or F2)
- Geophysical conditions
- Output fields desired

OUTPUT

Densities (#/cm3)
- O
- O2
- N2
- Total mass (g / cm3)

Mixing ratios
- O
- N2

Winds (m/s)
- Neutral zonal
- Neutral meridional
- Ion zonal
- Ion meridional
- Vertical

Temperature (K)
- Neutral

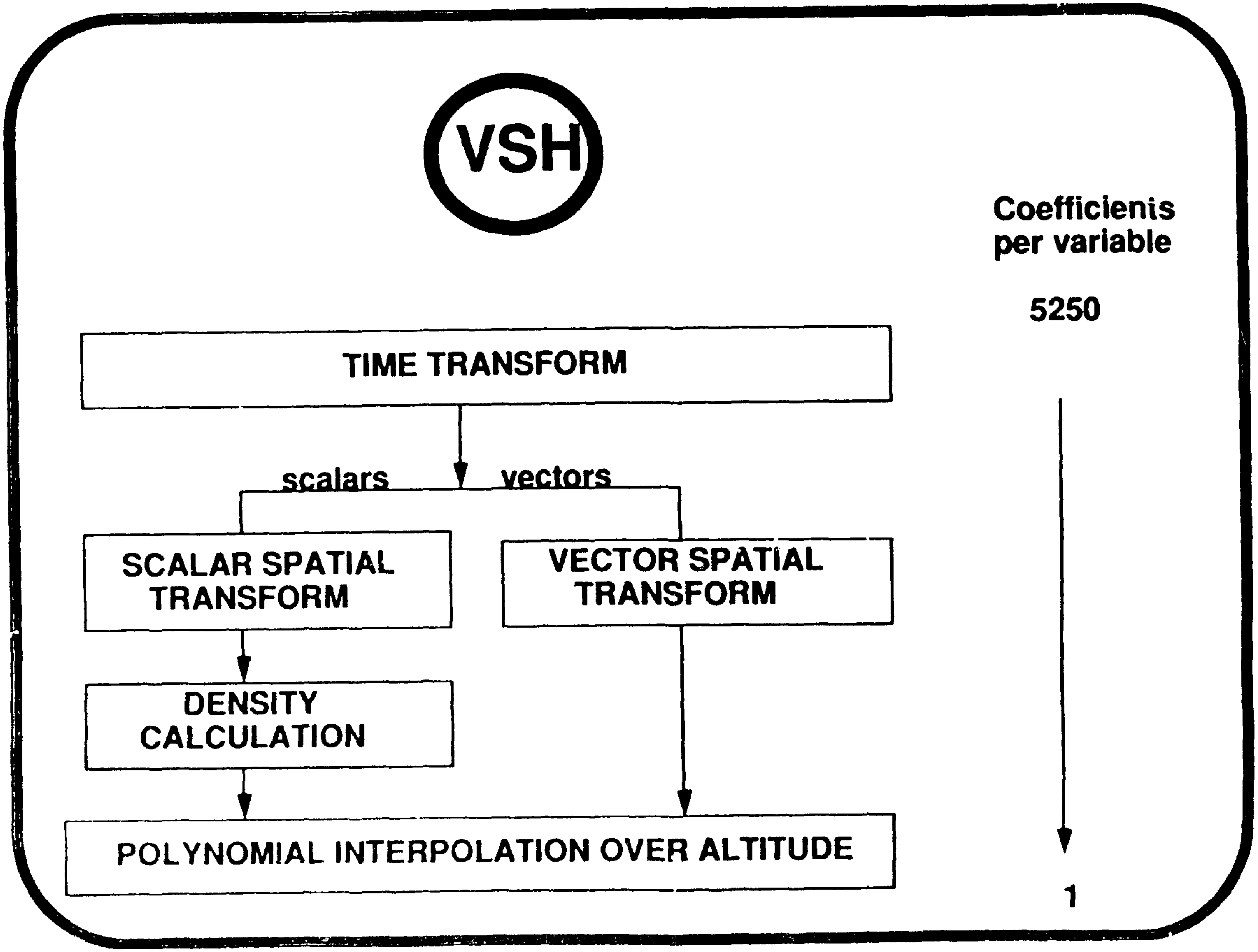
Height (km)
- Pressure surface (if applicable)

COEFFICIENT LIBRARY OF TIGCM RUNS

- Coefficient files are created on NCAR Cray based on output from TIGCM runs.
- The coefficient values are obtained by summing the projections of the output fields onto appropriate basis functions.
- Nine of the 13 variables are stored directly in coefficient files. The four densities are computed from the other field values.
- For each TIGCM run, there are 5250 coefficients per variable (or 47250 coefficients per run).
- Storage requirements per TIGCM run:
  - Binary Unformatted 187 K Bytes
  - ASCII Formatted 606 K Bytes

ONGOING DEVELOPMENT EFFORTS FOR COEFFICIENT LIBRARY

- Storing the mass density in a coefficient file will enable this field to be directly updated.



VSH-AFGL/AWS, Colorado Springs 1/29/90

RR6

TIME TRANSFORM

- Fourier time transform is carried out for each m,n, and z:

$$a_{m,n,z} = \frac{a_{0,m,n,z}}{2} + \sum_{k=1}^{T} a_{k,m,n,z} \cos kt + \sum_{k=1}^{T} b_{k,m,n,z} \sin kt$$

- Current truncation level is 7 time coefficients (T=3).
- The number of coefficients per variable is reduced from 5250 to 750.

VSH-AFGL/AWS, Colorado Springs 1/29/90

RR7

ONGOING DEVELOPMENT EFFORTS FOR TIME TRANSFORM

- The Fourier time representation assumes time periodicity.
- To model storm conditions, other basis representations will be explored (such as Chebyshev polynoimials).

SCALAR SPATIAL TRANSFORM

- Applies to scalar quantities: densities, temperature, height, and vertical velocity
- Scalar spherical harmonic expansion is carried out for each z level:

$$f(z) = \sum_{n=0}^{N-1} \sum_{m=0}^{\min(n,M-1)} (a_{n,m,z} \cos m\phi + b_{n,m,z} \sin m\phi) \; P_n^m(\cos\theta)$$

where $P_n^m(\cos\theta)$ is the associated Legendre function of order m
and degree n
evaluated at cos colatitude θ

- Truncation level is N=25 (meridional resolution),
  M= 5 (zonal resolution).
- The 750 coefficients (per variable) are reduced to 3.

VSH-AFGL/AWS, Colorado Springs 1/29/90

RR9

VECTOR SPATIAL TRANSFORM

- Applies to vector quantities (horizontal winds)

$$\begin{bmatrix} u(z) \\ v(z) \end{bmatrix} = \sum_{n=0}^{N-1} \sum_{m=0}^{\min(n,M-1)} \left(\vec{a}_{n,m,z} \cos m\phi + \vec{b}_{n,m,z} \sin m\phi\right) \begin{bmatrix} \frac{\partial P_n^m}{\partial \theta} \\ \frac{m P_n^m}{\sin \theta} \end{bmatrix}$$

where $P_n^m(\cos\theta)$ is the associated Legendre polynomial

- Truncation level is the same as for scalars.

ONGOING DEVELOPMENTAL EFFORTS FOR SPATIAL TRANSFORM

- Current truncation level is M= 5; N=25.

  - Representation of high latitude, low altitude winds for phase II requires high degree (i. e. large N) associated Legendre functions.

  - Alternative basis functions will be explored to optimize spatial variations at high altitude regions. Possibilities include empirical orthogonal functions and polar cap approximations.

  - A coordinate transformation will also be investigated.

- Truncation level has been optimized for winds. Scalar variables can probably use smaller N (reducing computational time and storage).

INTERPOLATION OVER ALTITUDE

- Values at three pressure surfaces are stored in coefficient files.
- VSH applies a least squares fit to each variable:
  - WINDS, HEIGHT:
    Quadratic fit
  - TEMPERATURE
    Bates fit (3-parameter)
  - DENSITIES:
    Linear fit in logarithms
- The three coefficients are reduced to a single output.

VSH-AFGL/AWS, Colorado Springs 1/29/90

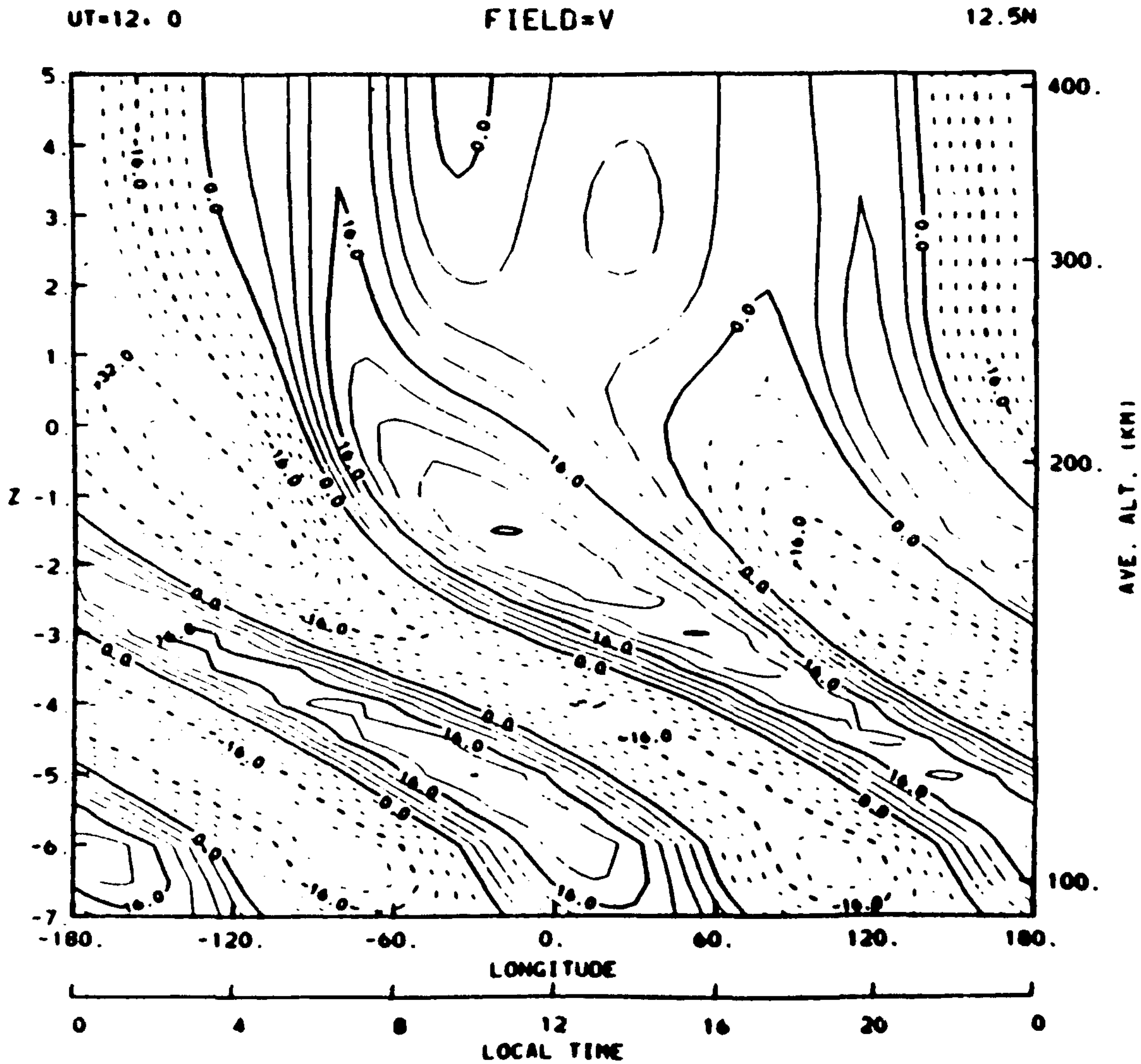
RR12

ONGOING DEVELOPMENT EFFORTS FOR ALTITUDE REPRESENTATION

- Need to retain more than three levels for calculation of altitude profile to properly model:
  - Scale height increase at higher altitudes
  - Tidal winds at lower altitudes

- Mathematical representations should vary with variable. Possible basis functions include:
  - Chebyshev Polynomials
  - Splines
  - Bates-type profile
  - Empirical Orthogonal Functions (EOF's)

EXAMPLE OF TIDAL WINDS



VSH-AFGL/AWS, Colorado Springs 1/29/90

Fig. 27

RR14

OUTPUT FIELD MODIFIER

- The parameters used in the vertical least squares fit are modified.

- Currently used for mass density updating

COEFFICIENT MODIFIER

- Not presently operational in VSH. Available only on the NCAR Cray to create new coefficient files.

- Currently used for modifying neutral winds

ONGOING DEVELOPMENT EFFORTS FOR COEFFICIENT FIELD MODIFIER AND OUTPUT FIELD MODIFIER

- High latitude winds show large variations over short distances. The radius of influence should be sensitive enough to vary with location.

- The objective analysis schemes will need to be consistent with modifications to the vertical representations.

VSH MODEL ACTION ITEMS

Response to Memo from DOAS (Capt. Osedacz, 5464), 10 October 1989

ACTION ITEMS	STATUS	COMMENTS
• Add output for mass density.	Closed	Mass density has been added as a 13th output variable.
• Provide coefficient files in ASCII format.	Closed	A conversion program has been included to convert the ASCII files to binary.
• Provide documentation of all library subroutines. Provide the units of all output variables.	Closed	Internal documentation is complete. Species densities are in #/cm3. Mass density is in g/ cm 3.
• Provide description of underlying physics and mathematics, including method of obtaining coefficients.	Open	A technical manual will be *prepared and will be updated* on a regular basis.

Summary of New Action Items

- Develop vertical representation (such as splines or EOF's) that make use of all 25 pressure surfaces; this will ensure accurate representation of tidal winds and scale height increases
- Develop field calculation modifier consistent with new vertical representation scheme
- Further refine objective analysis schemes
- Enable coefficient modification in VSH (rather than only on the Cray)
- Identify minimal number of spherical harmonics for scalars
- Optimize basis functions for auroral regions
- Consider modifications to Fourier time representation for storm events
- Write technical manual of VSH model

Appendix 3.4

Run Status

- Status of NCAR - TIGCM runs

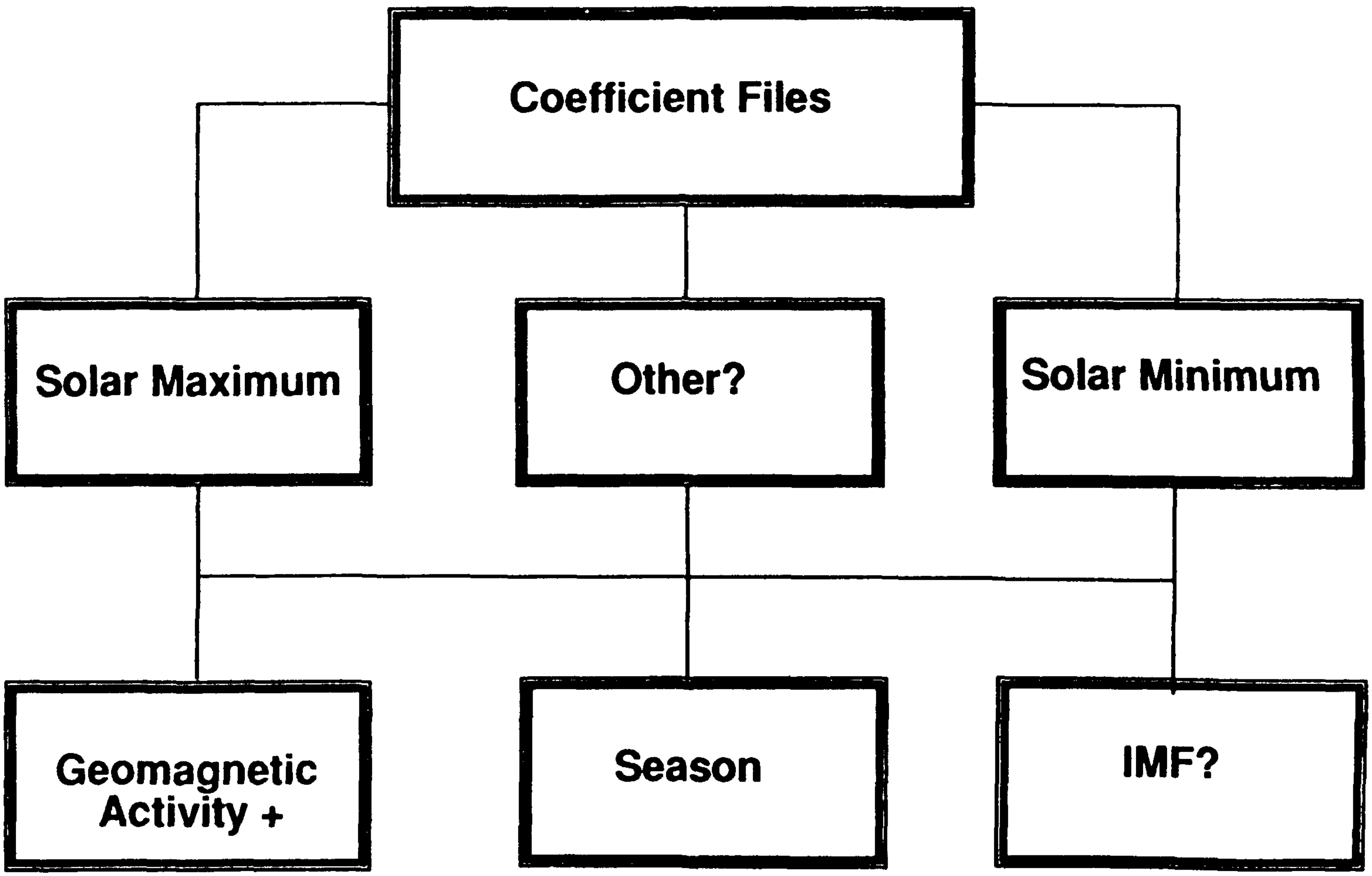
- Status of coefficient file production.

Aim of Selection

- We wish to produce a sufficiently large number of coefficient files to permit a smooth transition from one coefficient set to another.

- Therefore, we require a set of coefficients for different levels of geomagnetic activity, different parts of the solar cycle and different seasons. We may also have to deal with the transition between regimes and also the sign of the interplanetary magnetic field.

Selection Criteria



VSH - AFGL/AWS, Colorado Springs 1/28/90

AB 3

Status of New Runs (1. TIGCM Runs Made)

Solar Maximum: NH summer - 3 runs corresponding to
cross cap potential levels
of 30 kV, 60 kV and 90 kV

Solar Maximum: NH winter - 3 runs corresponding to
cross cap potential levels
of 30 kV, 60 kV and 90 kV

Solar Maximum: Equinox - 3 runs corresponding to
cross cap potential levels
of 30 kV, 60 kV and 90 kV

Solar Minimum: The same

Status of New Runs (2. Coefficient Files Made)

Solar Maximum: NH summer - 3 runs corresponding to cross cap potential levels of 30 kV, 60 kV and 90 kV

Solar Maximum: Equinox - 3 runs corresponding to cross cap potential levels of 30 kV, 60 kV and 90 kV

Solar Minimum: NH summer - 3 runs corresponding to cross cap potential levels of 30 kV, 60 kV and 90 kV

Solar Minimum: Equinox - 2 runs corresponding to cross cap potential levels of 60 kV and 90 kV

To By or not to By

- Changes in the y component of the interplanetary magnetic field (IMF) alter the ion convection pattern. This, in turn, affects the neutral circulation pattern, which, through advection affects neutral composition.

- The IMF is not continuously monitored at present.

- Changing geomagnetic activity can affect a large portion of the globe, but changes of IMF in the range normally observed affects only a limited region near the geomagnetic pole.

General

- We have enough runs to continue developing a semiempirical model of thermospheric density, and we will assess the number of further runs that are needed as we improve this model.

- Compositional changes during geomagnetic storms are complex and we are currently working to improve our understanding of them.

- We may not need to use IMF values to get a density model that is accurate on a global scale.

Appendix 3.5

VSH Objective Analysis

Through Objective Analysis, measured parameters (winds, density) can be used to modify TIGCM based VSH output fields.

Preliminary analysis scheme for ingestion of Dynamics Explorer neutral wind data into VSH is completed

- Average winds at high latitude in both hemispheres binned according to By, Kp

- Bin averaged data set merged together with TIGCM results for corresponding geophysical conditions

- New VSH library coefficient files created based on revised TIGCM/DE data set

- Improvements may be necessary

Objective Analysis of Winds

- A Semi-empirical model of thermosphere dynamics has been developed by merging data from the Dynamics Explorer-2 spacecraft with predictions from the NCAR-TIGCM. An objective analysis scheme was used for the data ingestion.

- To provide for sufficient coverage, the assumption was made that the neutral circulation pattern above 40° latitude was invariant in UT when described in geomagnetic coordinates. A Cressman weighting scheme was used below 40° latitude with a relaxation distance of 25° latitude, great circle distance

- Models for four different situations were obtained in spectral coefficient form 1) By positive, low Kp; 2) By positive, high Kp; 3) By negative, low Kp; 4) By negative, high Kp.

- Comparisons with experimental neutral wind data from DE and from independent ground-stations indicate satisfactory performance for the solar maximum, winter solstice model.

OBJECTIVE ANALYSIS SCHEME

A. Below 40° latitude

Use of Cressman distance weighting:

$$W(s) = \frac{d^2 - s^2}{d^2 + s^2}; \qquad s < d$$

$$= 0 \qquad ; \qquad s \geq d$$

With single influence radius, d = 25° (great circle distance)

B. Above 40° latitude

Use binned averaged neutral wind fields from DE-2 for November 1981 - January 1982 and November 1982 - January 1983, inclusive.

Assume invariance of neutral wind pattern in geomagnetic coordin ıtes. Direct splice of averaged data to TIGCM wind field.

C. Smoothing

Use regular vector spherical harmonic truncation scheme

DE-2 NEUTRAL WIND BINNING CRITERIA

- Geomagnetic bins of 1hr in MLT by 5° in MLAT
- Average over all UTs
- $Bz \leq 1.0$ for past 2 hrs.

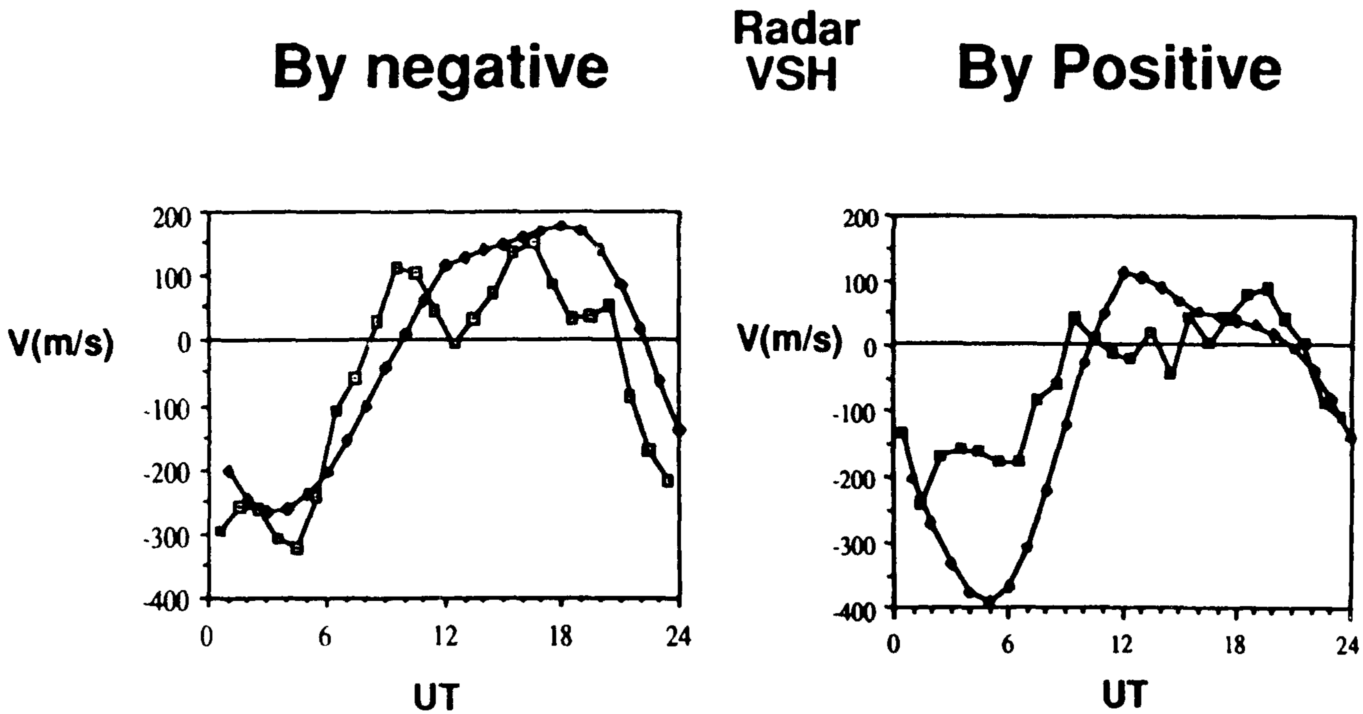
NUMBER OF ORBITS IN EACH CASE

• $Kp \leq 3.0$, $By > 0.0$	# of Orbits = 358
• $Kp > 3.0$, $By < 0.0$	# of Orbits = 262
• $3.0 < Kp < 6.0$, $By > 0.0$	# of Orbits = 262
• $3.0 < Kp < 6.0$, $By \leq 0.0$	# of Orbits = 126

VSH - AFGL/AWS, Colorado Springs 1/28/90

RJ 4

Comparison of Averaged (1983-88) Sondrestrom ISR and VSH Model Meridional Neutral Wind



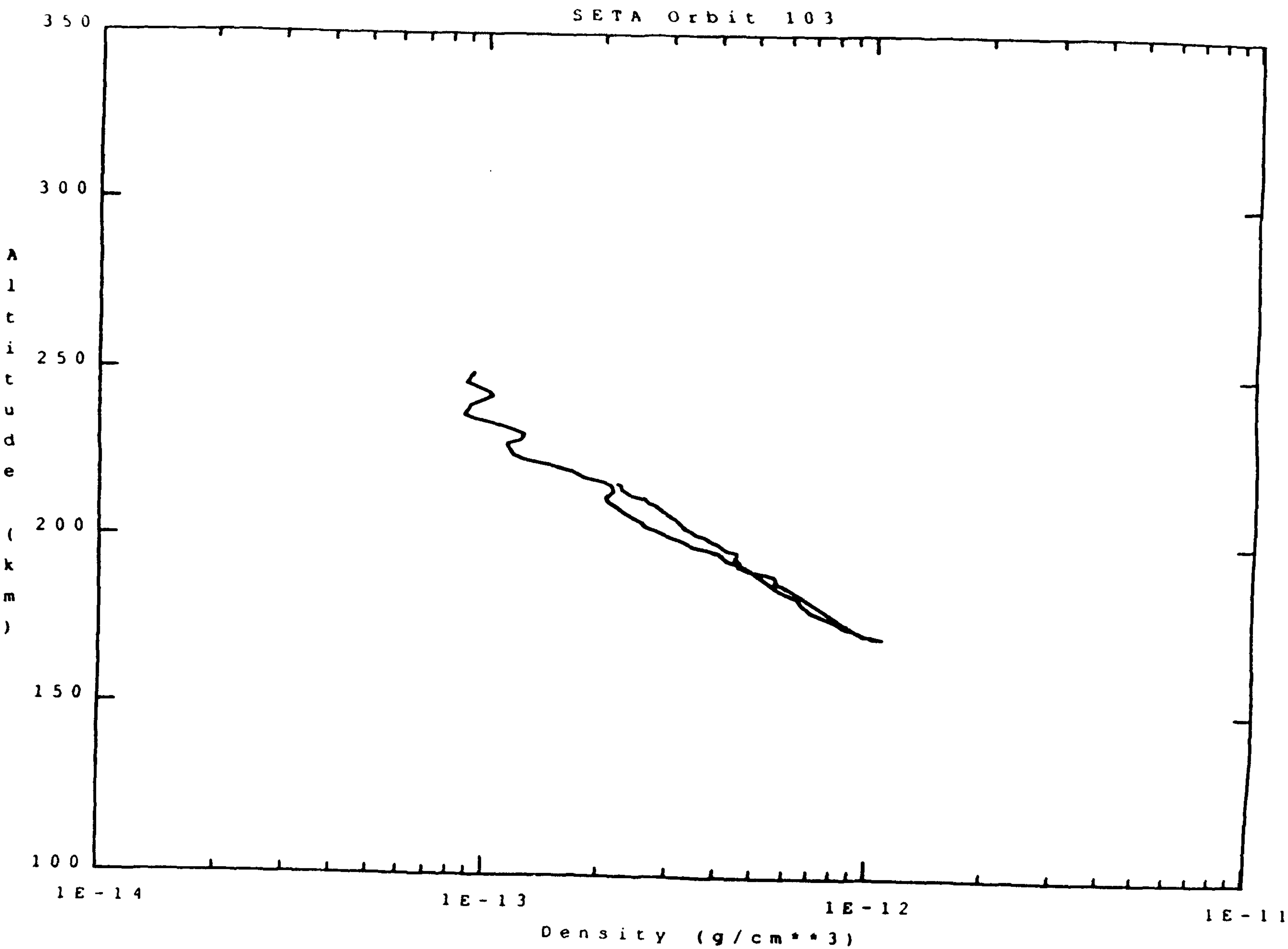
VSH - AFGL/AWS, *Colorado Springs 1/28/90*

RJ 9

Fig. 28

Objective Analysis of Neutral Density

- Neutral density $\rho(z,t,\theta,\phi)$
- Initially, consider only variation of measured ρ with z
- Fit observed neutral density profile along spacecraft trajectory.
- Adjust VSH results along the same trajectory for the appropriate geophysical conditions such that altitude profile of VSH results agrees with observed density profile.



SETA Orbit 103
350
300
250
200
150
100
Altitude (km)
1E-14
1E-13
1E-12
1E-11
Density (g/cm**3)

Fig. 29

Objective Analysis of Neutral Density

The neutral density profile can be represented by

$$\ln \rho = a_0 + a_1 z$$

where the slope a_1 is given by

$$\frac{d \ln \rho}{dz} = \tan \theta$$

Objective Analysis of Neutral Density

- Fit measured SETA density profile to get a_{0s}, a_{1s} describing trajectory as a whole.

- Evaluate VSH along the same trajectory and fit the resulting density profile to get a_{0v} and a_{1v} corresponding to the VSH results along the entire trajectory.

- Adjust VSH density profile to the SETA profile linear fit by:

    1) finding residual of VSH density relative to linear fit to VSH profile at all points along spacecraft trajectory

    2) adding the residual intercept and slope to the SETA profile

Objective Analysis of Neutral Density

Then the adjusted density ρ' is given by

$$\ln \rho' = (a_0 - a_{0v}) + a_{0s} + z \tan\left[(\tan^{-1}\theta - \tan^{-1}\theta_v) + \tan^{-1}\theta_s\right]$$

where a_0, θ_0 are fit parameters for individual VSH profiles at a given t, θ, ϕ

a_{0v}, θ_v are the fit parameters for the linear fit to the VSH profile along the spacecraft trajectory;

a_{0s}, θ_s are the fit parameters for the linear fit to the SETA density profile

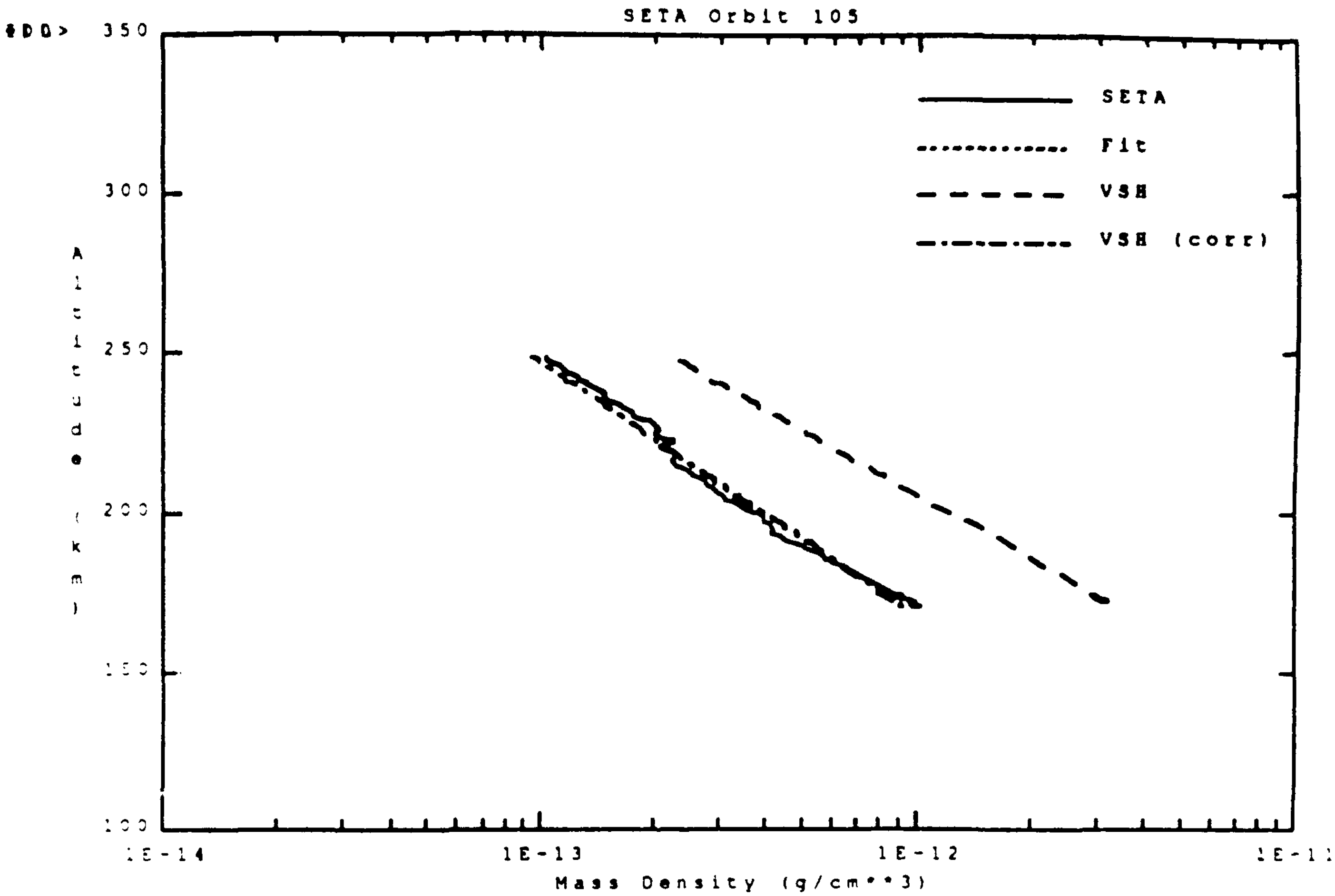

SETA Orbit 105
SETA
Fit
VSH
VSH (corr)
Altitude (km)
Mass Density (g/cm**3)
350
300
250
200
150
100
1E-14
1E-13
1E-12
1E-11

Fig. 30

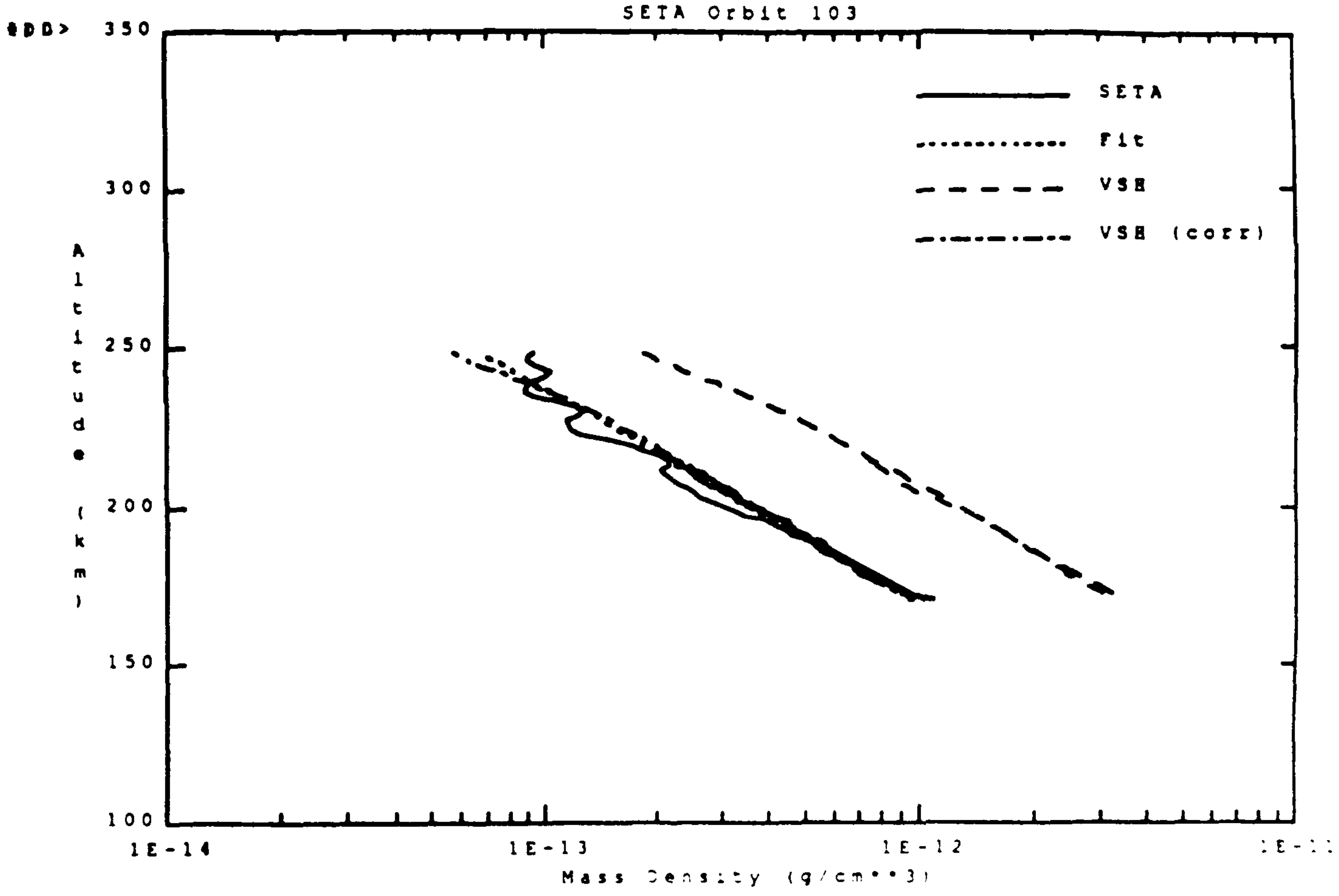

@DD>
SETA Orbit 103
SETA
Fit
VSH
VSH (corr)
350
300
250
200
150
100
Altitude (km)
1E-14
1E-13
1E-12
Mass Density (g/cm**3)

Fig. 31

Objective Analysis of Neutral Density

- Preliminary objective analysis technique has been developed to modify TIGCM output on basis of satellite measured densities.
- Improvements will be necessary to adjust profile on basis of data acquired over wider altitude range.
- Fit to data will default to TIGCM adjusted to match MSIS absolute density at low altitude and to MSIS augmented by exospheric H model above maximum TIGCM altitude.

Objective Analysis of Neutral Density

Action Items

- Modify technique to adjust VSH results over 250-1500 km altitude range
  - change functional form from linear to form more descriptive of expected profiles (quadratic, etc.)
  - include TIGCM adjusted to MSIS at low altitude and MSIS + exospheric H above TIGCM maximum altitude
- Develop technique to modify density field including latitudinal, longitudinal, and universal time dependences
- Implement total density coefficient modifier
- Consider region of influence for perturbations on average profile

<u>**Appendix 3.6**</u>

TIGCM Developments

1. Solar EUV/UV Flux Model

   - Based on $F_{10.7}$ and $\bar{F}_{10.7}$ (Hinteregger data)
   - Based on Lyman -α and $F_{10.7}$ (SME data and Hinteregger data)
   - Compared with recent rocket measurements
   - Largest uncertainties at $\lambda < 20$ nm (important for E-region, n_e and NO)

2. Improved Auroral Model

   - Evans and Fuller-Rowell particle precipitation
   - Convection model

     a) Heelis, analytical
     b) Maynard and Rich, analytical
     c) Emery modifications for time-dependent forcings
     d) AMIE

   - Needs considerable development for time-dependent forcings

3. Magnetosphere/Ionosphere Plasma and Energy Exchange

   - Considerable improvements achieved by specifying fluxes
   - Empirical parameterizations used
   - Need to develop physical/interactive model

4. Tidal Boundary (Semi-Diurnal Tides)

   - Amplitude and phases from Vial/Forbes model for each month of the year
   - Verified with data (except September tides)

TIGCM Developments (Cont.)

5. Introduced 1-1 Tide into TIGCM
   - Important for lower thermosphere
   - Amplitude and phase not well defined

6. Included Viscous Heating into TIGCM Thermodynamic Equation (~ 1-2% Changes in Density)

7. Improve Specification of Height of Constant Pressure Surface
   - Introduce variable gravity (~ 30 km at upper B.C.)
   - TIGCM densities were previously high relative to data and MSIS-86
   - Much better agreement with variable gravity
   - Future improvements require connection with lower atmosphere (model atmosphere to specify heights)
   - Normalization is improved but needs further development

8. Improve TIGCM Processors
   - Comparisons with data and MSIS-86
   - Analysis of physical processes
   - Rapid visualizations

TIGCM Validation

A great deal of progress has been made in substantiating the TIGCM performance against real data and also in documenting TIGCM performance versus MSIS-86 model predictions. At least five papers are in various stages of publication documenting TIGCM performance. In addition, the model is being used by at least eight different scientific collaborators to verify model performance by comparison with various ground based measurements which include:

a) Effect of tides from the lower atmosphere on thermospheric densities -- Fesen, U. of Colorado; Forbes, Boston U.

b) Ionospheric storm perturbations -- Codrescu, Boston U.; Crowley, Lowell U.

c) Airglow emissions -- Solomon, NCAR

d) Thermospheric density and composition -- Burns and Killeen, U. of Michigan

e) Vorticity and divergent flows -- Thayer and Killeen, U. of Michigan

f) Nitric oxide -- Fesen, U. of Colorado; Gerard, U. of Leige

g) South polar cap dynamics -- Smith, U. of Alaska; Hernandez, U. of Washington

h) Radar derived winds -- Wickwar, Utah State; Hagan, Millstone Hill; Burnside, Arecibo Obs.

All of these studies are providing inputs to help validate model performance and suggest areas where further TIGCM improvements are necessary to achieve the Air Force overall density goals. The specific case studies that are underway include:

a) March 21 - April 10, 1979 -- SETA, radar data

b) January 21-31, 1983 -- Comprehensive DE measurements

c) February 4-9, 1986 major storm -- Aerospace airglow and radar measurements

d) September 20-28, 1984 -- ETS study

e) March 13-14, 1989 major storm

f) LTCS, September 21-25, 1987, December 5-10, 1988 period

plus there are others associated with CEDAR, WITS, and DE.

TIGCM Studies in Progress

1. TIGCM Sensitivity Studies

   a) Increase solar EUV by 10%
   b) Decrease solar EUV by 10%
   c) Change *By* from 0 to +10
   d) Change *By* from 0 to -10
   e) Change Φ from 40 to 50 kV
   f) Change Φ from 40 to 30 kV

      1) Solar min; March equinox, December solstice
         $F_{10.7} = 67$, $\bar{F}_{10.7} = 72$, $P = 5$ GW, $\Phi = 40$ kV
      2) Solar max; December solstice
         $F_{10.7} = 243$, $\bar{F}_{10.7} = 215$, $P = 11$ GW, $\Phi = 60$ kV

   g) Increase solar SRC by 10%
   h) Change tidal specification

   - Results are presented as % difference from unperturbed run

2. TIGCM/MSIS-86 Comparisons

   - 18 TIGCM cases have been run for density model development
   - Develop normalization scheme

3. Continue March 1979 Study using SETA Data

   - 20 day run, March 20 - April 10, 1979
   - Percentage errors from SETA measurements
     a) TIGCM
     b) MSIS-86

4. DE Satellite Study, January 20-30, 1983

   - T_n, $\bar{V}_n$, n_n, n_e, T_e, comparisons along satellite track

```
----------
I HAVE MADE TIGCM RUNS FOR A CONSISTENT SET TO BE USED IN AIR FORCE
DENSITY SPECIFICATION MODEL DEVELOPMENT:
A. SOLSTICE SOLAR MINIMUM DAY=76355,F107=67,F107A=72
      DATA=ROBLE/RGR88/DVWSOL
     1.P=5GW,CTPOTEN=30KV
       HISTORY=ROBLE/RGR90/SOLN01,02 FROM 1,0,0 TO 2,0,0 HOURLY
     2.P=11GW,CTPOTEN=60KV
       HISTORY=ROBLE/RGR90/SOLN11,12 FROM 1,0,0 TO 2,0,0 HOURLY
     3.P=33GW,CTPOTEN=90KV
       HISTORY=ROBLE/RGR90/SOLN21,22 FROM 1,0,0 TO 2,0,0 HOURLY
B. SOLSTICE SOLAR MAXIMUM DAY=79355,F107=243,F107A=215
     1.P=5GW,CTPOTEN=30KV
       HISTORY=ROBLE/RGR90/SOLX01,02 FROM 1,0,0 TO 2,0,0 HOURLY
     2.P=11GW,CTPOTEN=60KV
       HISTORY=ROBLE/RGR90/SOLX11,12 FROM 1,0,0 TO 2,0,0 HOURLY
     3.P=33GW,CTPOTEN=90KV
       HISTORY=ROBLE/RGR90/SOLX21,22 FROM 1,0,0 TO 2,0,0 HOURLY
C  EQUINOX SLOAR MINIMUM DAY=76080,F107=67,F107A=72.
     1.P=5GW,CTPOTEN=30KV
       HISTORY=ROBLE/RGR90/EQSN01,02 FROM 1,0,0 TO 2,0,0 HOURLY
     2.P=11GW,CTPOTEN=60KV
       HISTORY=ROBLE/RGR90/EQSN11,12 FROM 1,0,0 TO 2,0,0 HOURLY
     3.P=33GW,CTPOTEN=90KV
       HISTORY=ROBLE/RGR90/EQSN21,22 FROM 1,0,0 TO 2,0,0 HOURLY
D. EQUINOX SOLAR MAXIMUM DAY=79080,F107=243,F107A=215
     1.P=5GW,CTPOTEN=30KV
       HISTORY=ROBLE/RGR90/EQSX03,04 FROM 1,0,0 TO 2,0,0 HOURLY
     2.P=11GW,CTPOTEN=60KV
       HISTORY=ROBLE/RGR90/EQSX11,12 FROM 2,0,0 TO 3,0,0 HOURLY
     3.P=11GW,CTPOTEN=90KV
       HISTORY=ROBLE/RGR90/EQSX21,22 FROM 1,0,0 TO 2,0,0 HOURLY
E. SUMMER SOLSTICE SOLAR MINIMUM DAY=76182,F107=67,F107A=72
     1.P=5GW,CTPOTEN=30KV
       HISTORY=ROBLE/RGR90/SUMN05,06 FROM 2,0,0 TO 3,0,0 HOURLY
     2.P=11GW,CTPOTEN=60KV
       HISTORY=ROBLE/RGR90/SUMN13,14 FROM 3,0,0 TO 4,0,0 HOURLY
     3.P=33GW,CTPOTEN=90KV
       HISTORY=ROBLE/RGR90/SUMN23,24 FROM 3,0,0 TO 4,0,0 HOURLY
F. SUMMER SOLSTICE SOLAR MAXIMUM DAY=79182,F107=243,F107A=215
     1.P=5GW,CTPOTEN=30KV
       HISTORY=ROBLE/RGR90/SUMX01,02 FROM 1,0,0 TO 2,0,0 HOURLY
     2.P=11GW,CTPOTEN=60KV
       HISTORY=ROBLE/RGR90/SUMX11,12 FROM 1,0,0 TO 2,0,0 HOURLY
     3.P=33GW,CTPOTEN=90KV
       HISTORY=ROBLE/RGR90/SUMX21,22 FROM 1,0,0 TO 2,0,0 HOURLY
(NOTE THAT THE NEW MODEL/RGR90/HISTORIES ARE UT=MODEL TIME(FINALLY)
----------
```

Critical Inputs Required during Quiet Geomagnetic Activity

Thermosphere/Ionosphere System

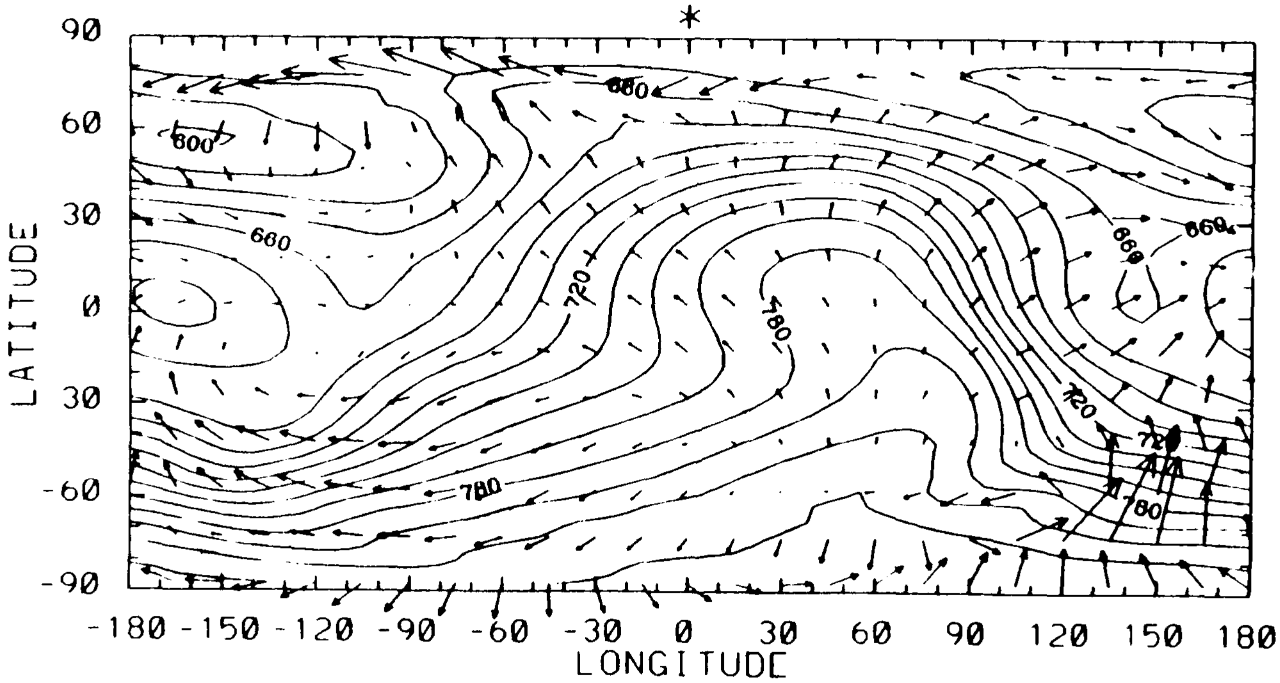
Zero Order	First Order	Higher Order
Solar EUV/UV $5 < \lambda < 200$ nm		
	Particle Precipitation (GW)	
	Cross-Cap Potential (kV)	
		Bz, By, Configuration of Potential Pattern
	Tidal Amplitudes and Phases	
Density Measurements (normalization)		
		Magnetosphere/Ionosphere Plasma and Energy Exchange

Critical Inputs Required during Disturbed Geomagnetic Activity

Thermosphere/Ionosphere System

Zero Order	First Order	Higher Order
	Solar EUV/UV $5 < \lambda < 200$ nm	
Particle Precipitation (GW)		
Cross-Cap Potential (kV)	Bz, By, Configuration of Potential Pattern	
	Magnetosphere/Ionosphere Plasma and Energy Exchange	
		Tidal Amplitudes and Phases
Density Measurements (normalization)		

TIGCM NEUTRAL TEMPERATURE (DEG K)
SOLSTICE BASE CASE UT=12.0 HT=300.0 76355



MINIMUM 598.2, MAXIMUM 838.6, CONTOUR INTERVAL 15

400 M/S

Fig. 32

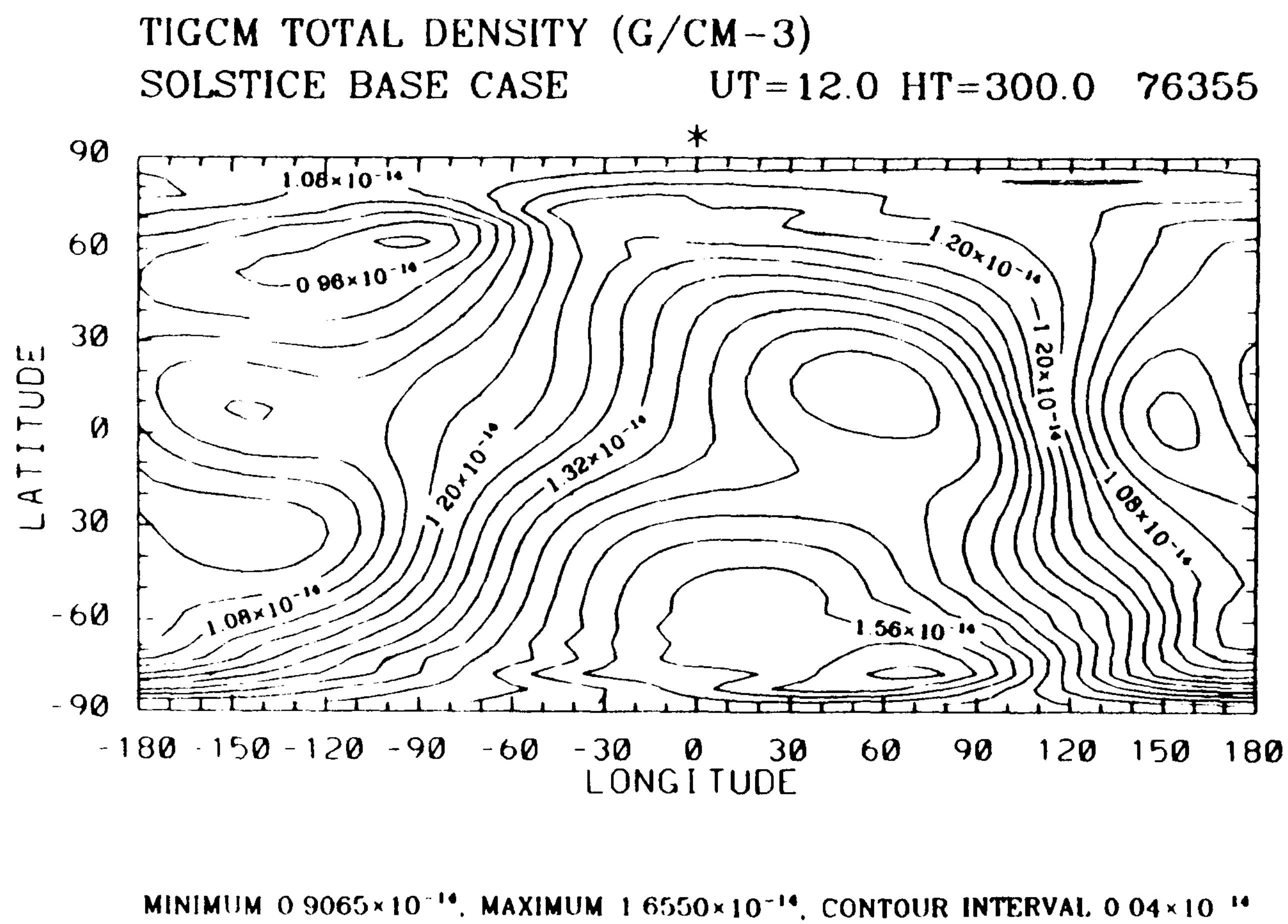
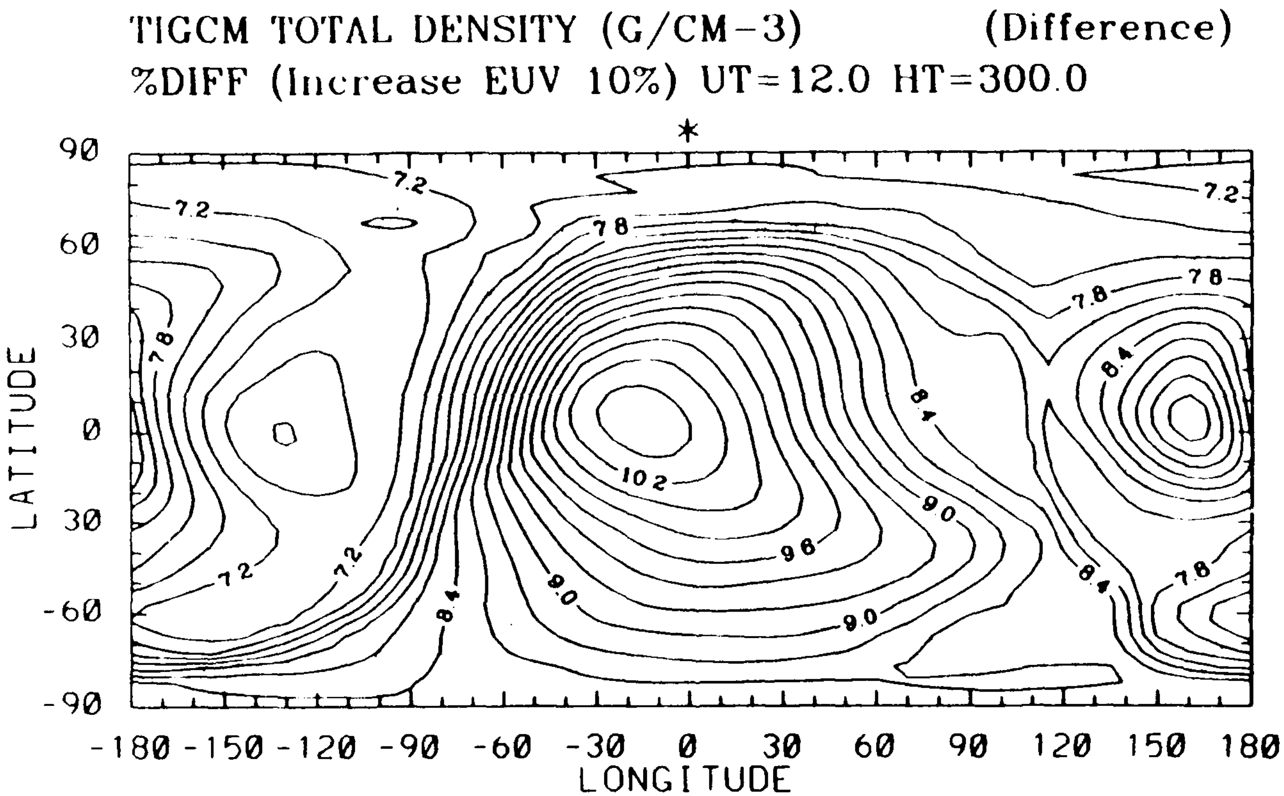

TIGCM TOTAL DENSITY (G/CM-3)
SOLSTICE BASE CASE UT=12.0 HT=300.0 76355
90
60
30
0
30
-60
-90
LATITUDE
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
LONGITUDE
1.08×10⁻¹⁴
0.96×10⁻¹⁴
1.20×10⁻¹⁴
1.32×10⁻¹⁴
1.56×10⁻¹⁴
MINIMUM 0.9065×10⁻¹⁴, MAXIMUM 1.6550×10⁻¹⁴, CONTOUR INTERVAL 0.04×10⁻¹⁴

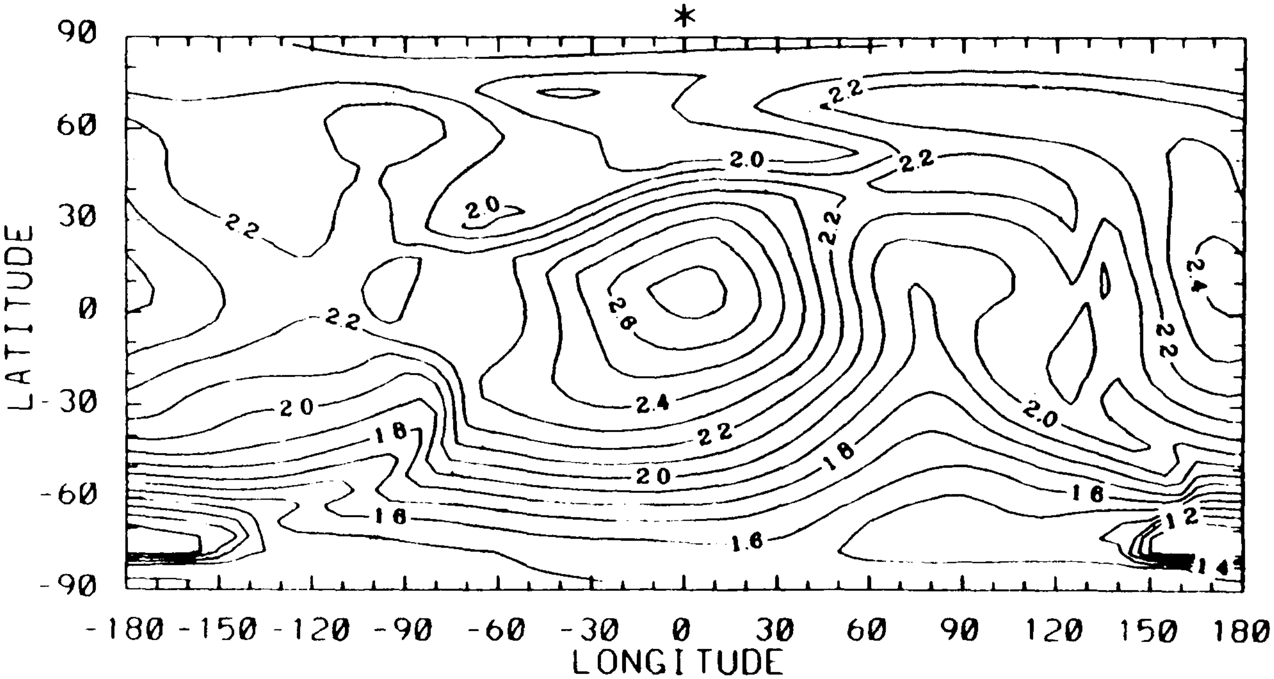
Fig. 33



MINIMUM 6.789, MAXIMUM 10.505, CONTOUR INTERVAL .2

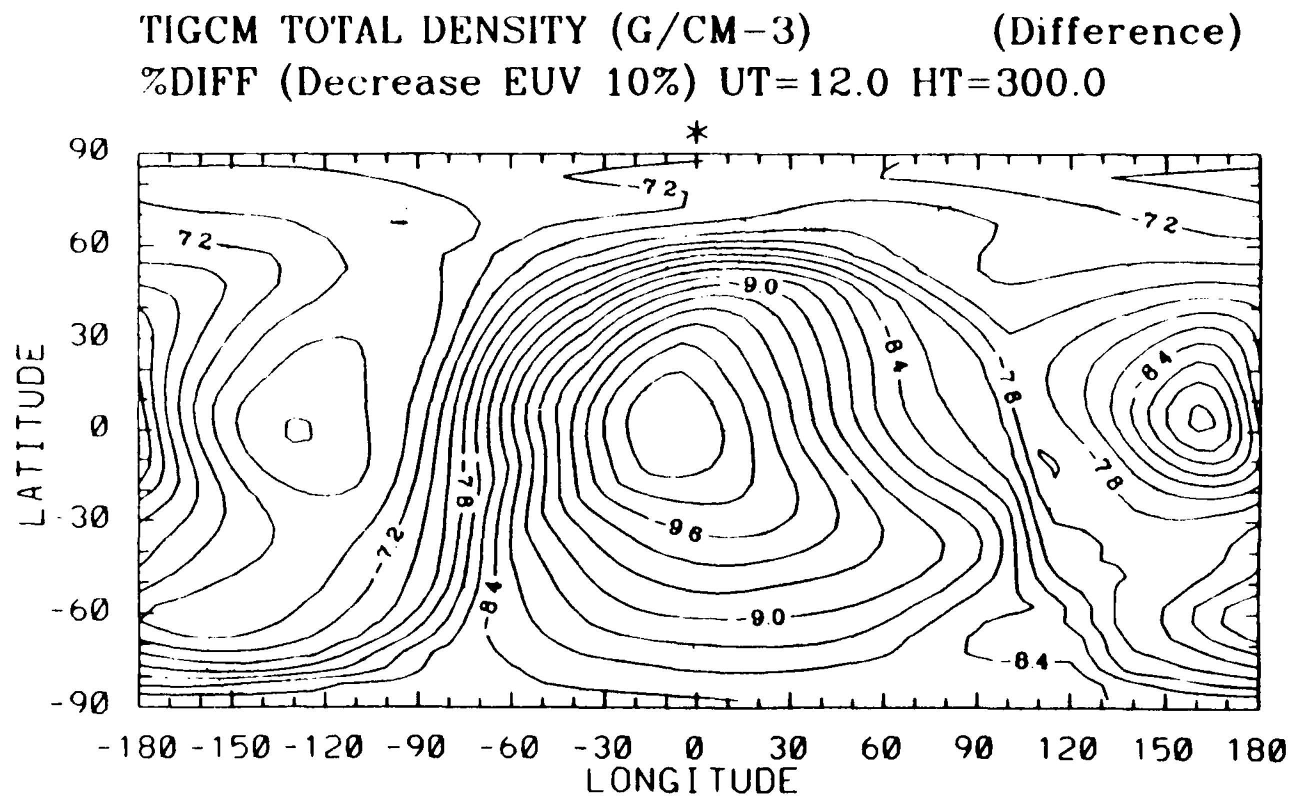
Fig. 34

TIGCM TOTAL DENSITY (G/CM-3) (Difference)
%DIFF (Increase EUV 10%) UT=12.0 HT=200.0



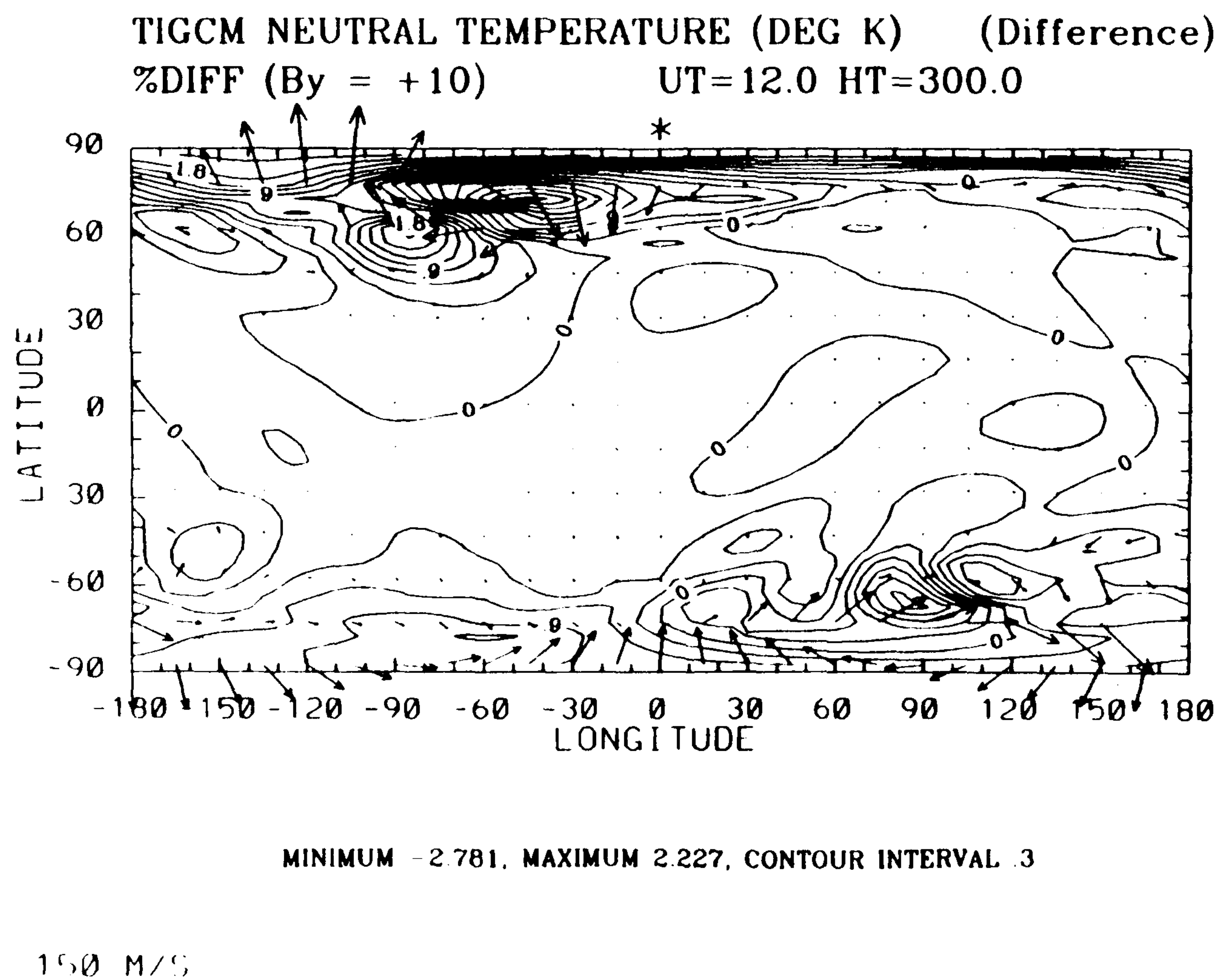
MINIMUM 1.017, MAXIMUM 2.740, CONTOUR INTERVAL .1

Fig. 35



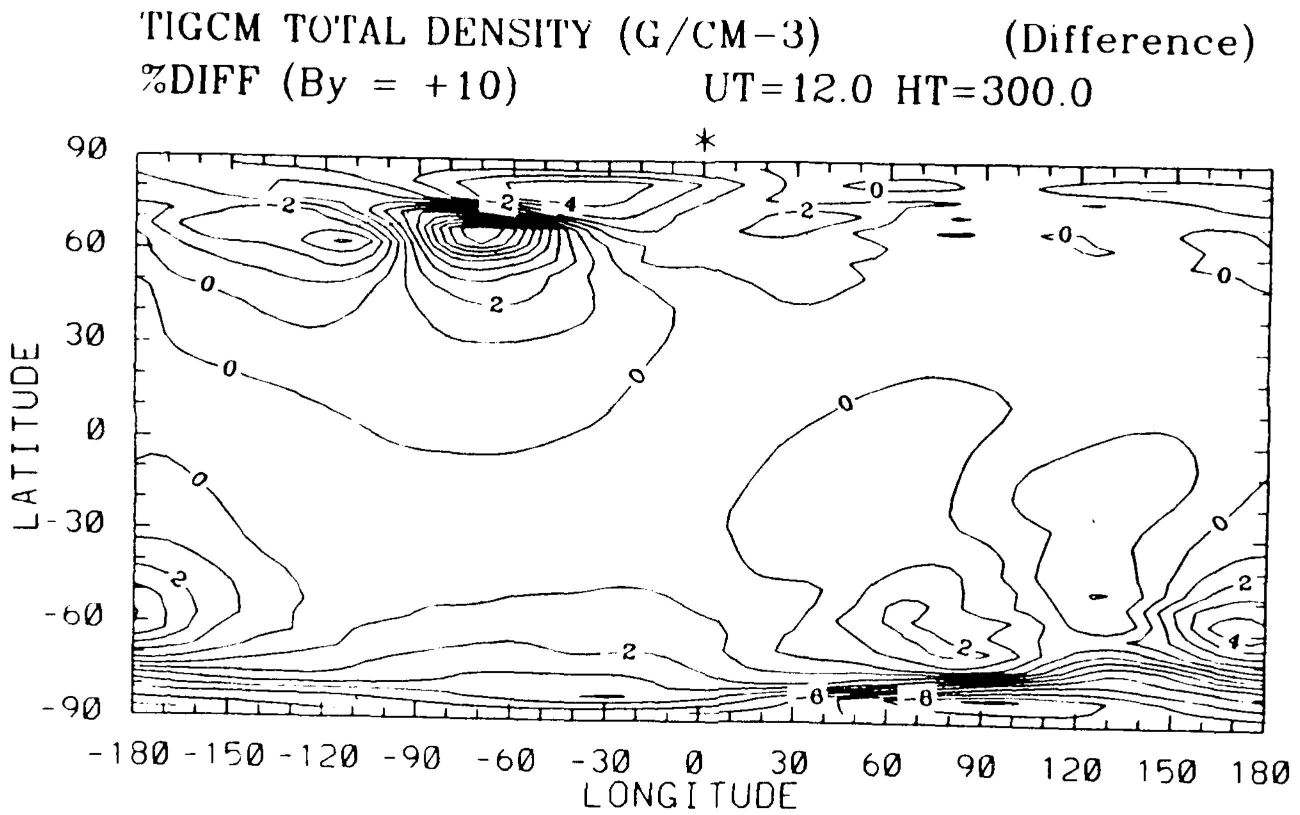
MINIMUM -10.193, MAXIMUM -6.588, CONTOUR INTERVAL .2

Fig. 36



MINIMUM -2.781, MAXIMUM 2.227, CONTOUR INTERVAL .3

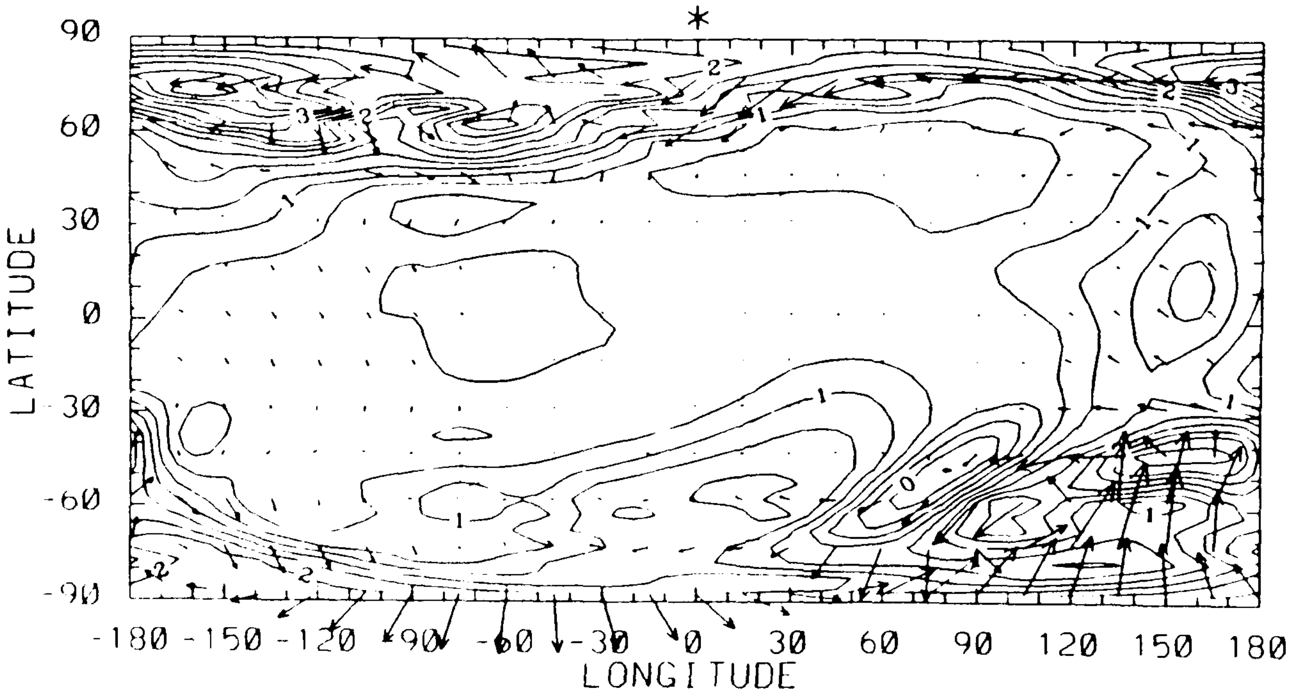
Fig. 37



MINIMUM −9.08, MAXIMUM 9.81, CONTOUR INTERVAL 1

Fig. 38

TIGCM NEUTRAL TEMPERATURE (DEG K) (Difference)
%DIFF (Potential = 50kV) UT=12.0 HT=300.0

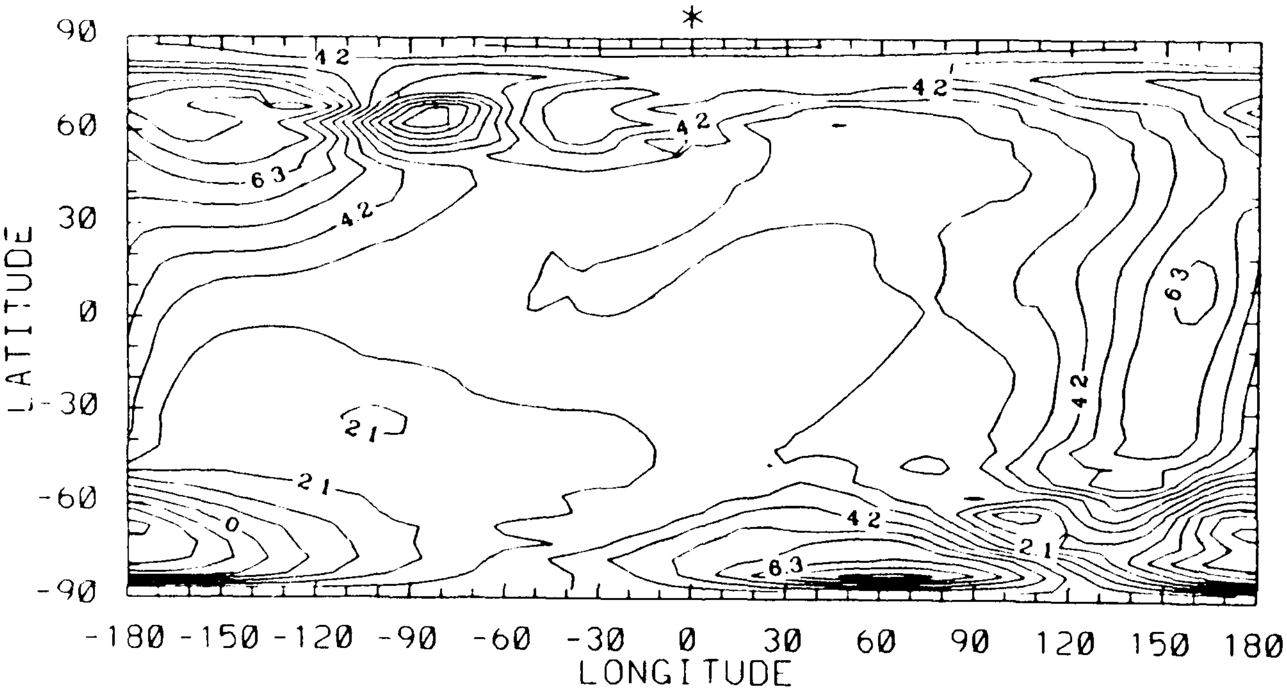


MINIMUM -.282, MAXIMUM 3.959, CONTOUR INTERVAL .25

80 M/S

Fig. 39

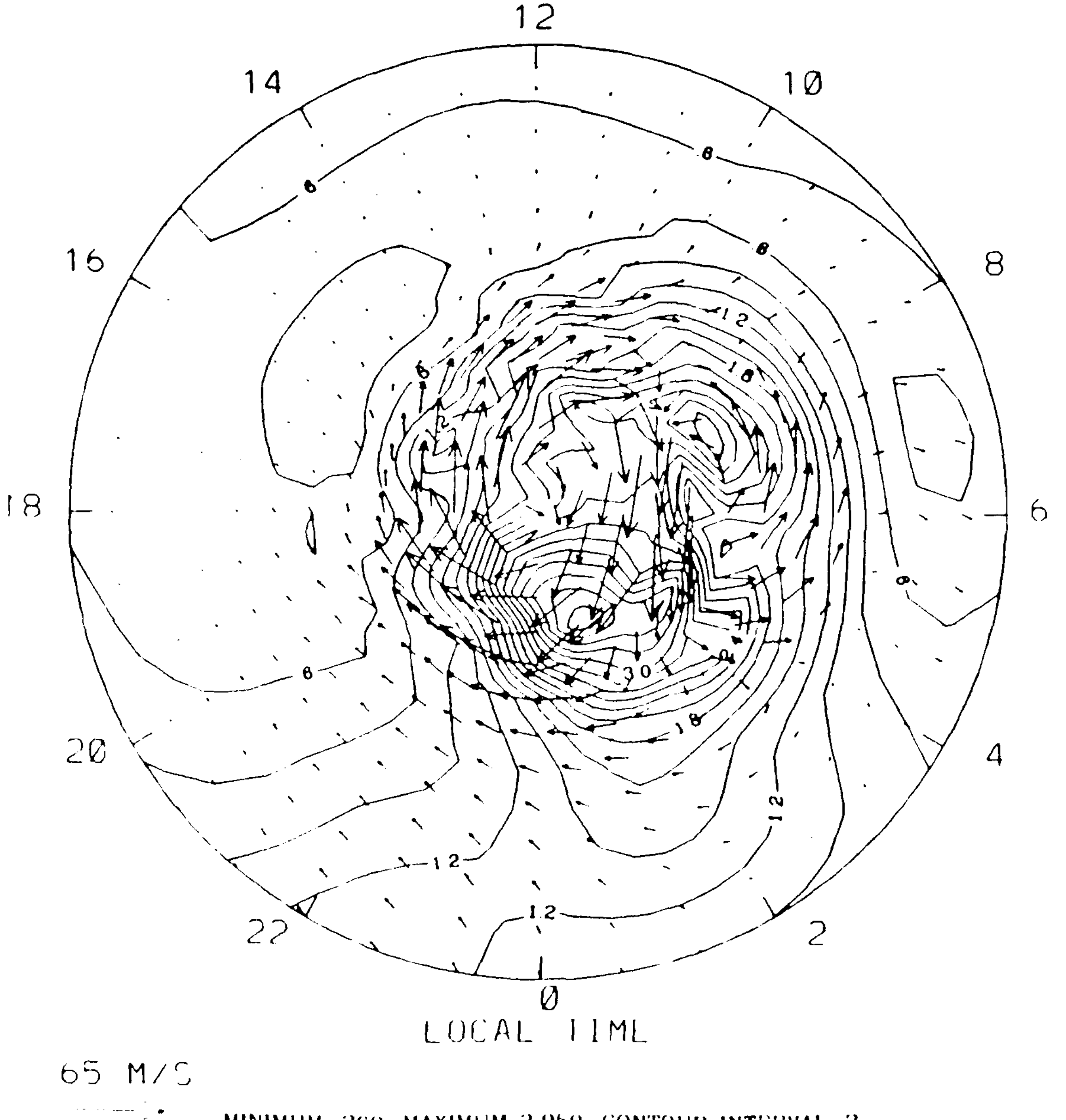
TIGCM TOTAL DENSITY (G/CM−3) (Difference)
%DIFF (Potential = 50kV) UT=12.0 HT=300.0



MINIMUM −2.397, MAXIMUM 8.331, CONTOUR INTERVAL .7

Fig. 40

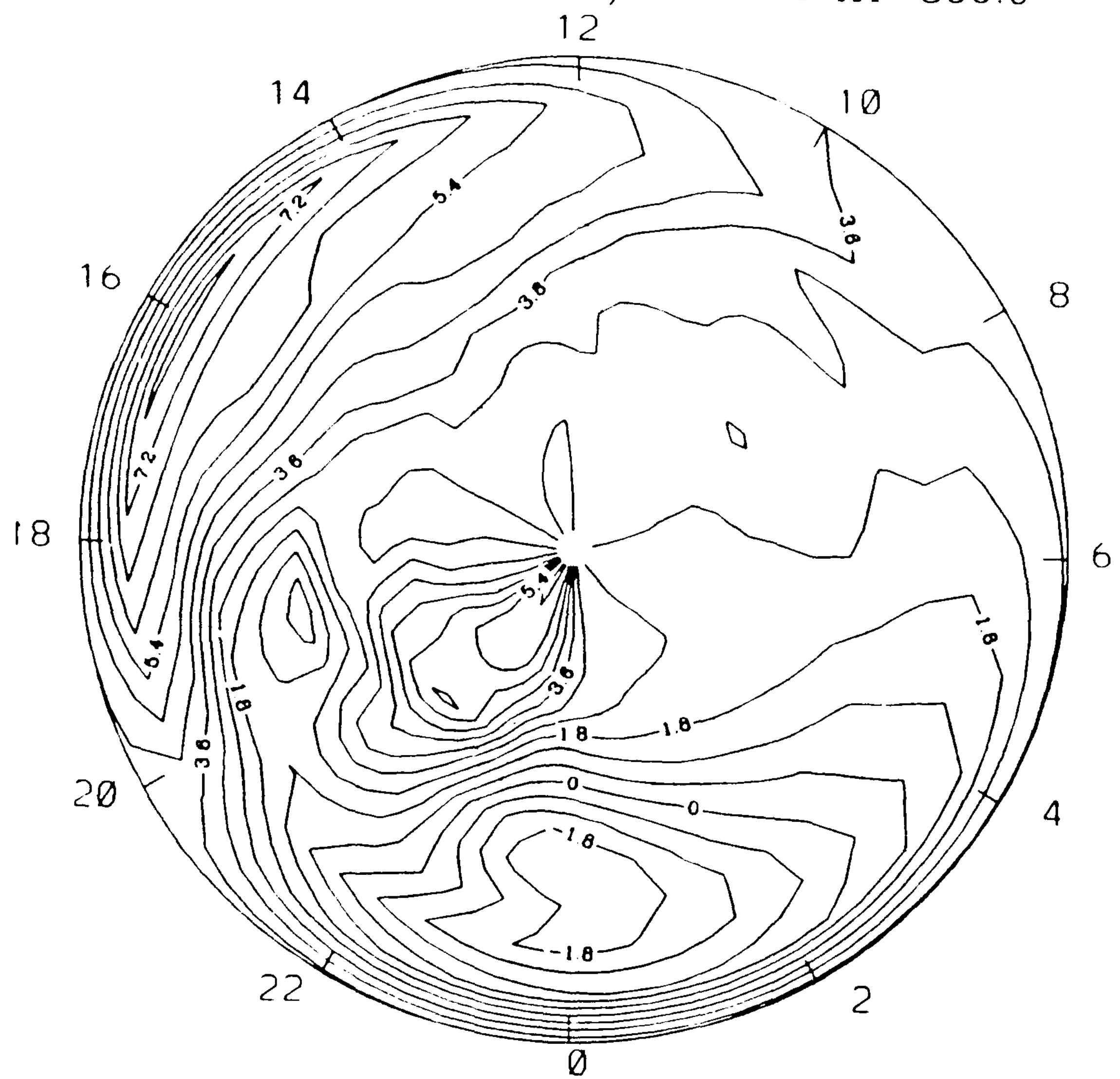
TIGCM NEUTRAL TEMPERATURE (DEG K) (Difference)
%DIFF (Potential = 50kV) UT=12.0 HT=300.0



MINIMUM .269, MAXIMUM 3.959, CONTOUR INTERVAL .2

Fig. 41

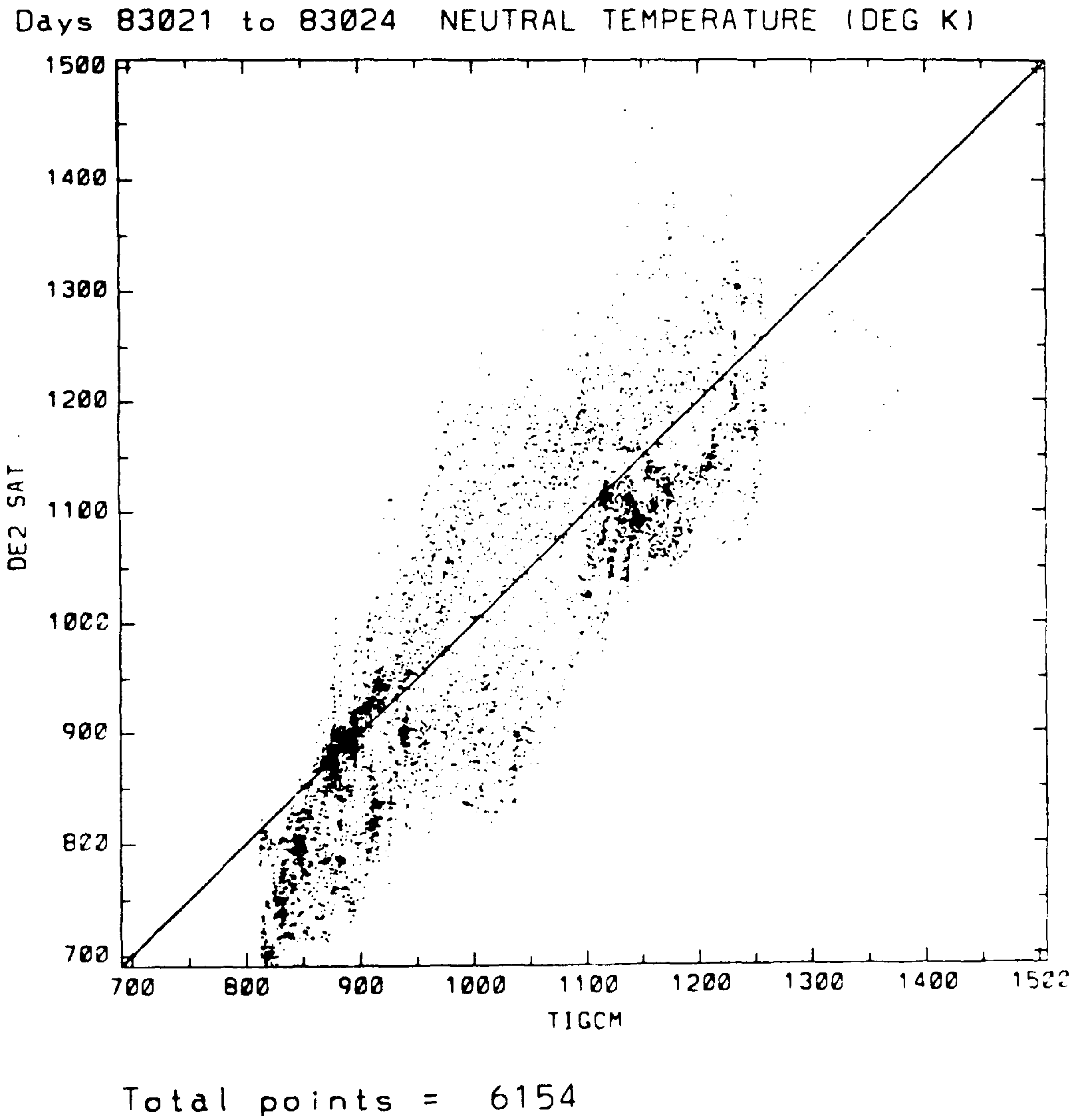
TIGCM TOTAL DENSITY (G/CM-3) (Difference)
%DIFF (Potential = 50kV) UT=12.0 HT=300.0



LOCAL TIME

MINIMUM -2.397, MAXIMUM 7.978, CONTOUR INTERVAL .6

Fig. 42



Days 83021 to 83024 NEUTRAL TEMPERATURE (DEG K)
1500
1400
1300
1200
1100
1000
900
800
700
DE2 SAT
700
800
900
1000
1100
1200
1300
1400
1500
TIGCM
Total points = 6154

Fig. 43

Summary and Conclusions

- Considerable Improvement in TIGCM Physical Processes

  a) Viscous heating

  b) O^+ plasma exchange

  c) Tidal specifications

  d) etc.

- Performed a Large Number of Sensitivity Studies

  a) Solar EUV variations

  b) Solar SRC variations

  c) By and Φ variations

  d) Tides

  e) Others

- Improved TIGCM Normalization; Better Agreement with Data

- Continued with Data Validation Studies; Significant TIGCM Improvements

Appendix 3.7

Major Action Items For Next 3 Month Period

- Incorporate neutral hydrogen model above 500 km.
- Incorporate MSIS default scheme.
- Continue development and implementation of library scheme for Phase I model delivery.
- Deliever second preliminary test version to Space Forecast Center for continuing evaluation.
- Further coordination with ionospheric modeling effort.

Summary

- ➡ Intensive development of Phase I model underway for delivery at end of FY-90
- ➡ Density objective analysis: initial scheme implemented and tested; Further refinement necessary
- ➡ Coding and documentation efforts underway: Helpful interactions with Space Forecast Center. Coordination with Ionospheric Modeling Group
- ➡ TIGCM frozen and multiple sets of runs have been carried out. Library of coefficient files growing
- ➡ University of Michigan team in place with established responsibilities

4.0 Quarterly Status Report #4: 1 January 1990 - 31 March 1990

THE UNIVERSITY OF MICHIGAN

SPACE PHYSICS RESEARCH LABORATORY

Quarterly Status Report # 4
Covering the Period 1 January 1990 through 31 March 1990
University of Michigan Account 080063

DEVELOPMENT OF A VECTOR SPHERICAL HARMONIC (VSH) MODEL OF THE NEUTRAL THERMOSPHERE

by

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AFGL Contract F19628-89-K-0026

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Air Force Geophysics Laboratory
Air Force Systems Command
L.G. Hanscom Air Force Base
Bedford, Massachusetts 01731

ATTN: Dr. Frank Marcos

Executive Summary

The Air Force has requirements for accurate knowledge and specification of the state variables of the Earth's thermosphere. Work done under this contract will lead to a new model of global thermospheric density that can be used to specify and forecast neutral densities, temperatures, and winds for a wide range of solar and geomagnetic activity. The model will be based on simulations made with the National Center for Atmospheric Research (NCAR) Thermosphere/Ionosphere General Circulation Model (TIGCM) and on data. It will be capable of using real-time geophysical indices or data from ground-based and satellite inputs and will provide neutral variables at specified locations and times in the altitude range 90 - 1500 km. This hybrid theoretical and semi-empirical model will be based on a new Vector Spherical Harmonic (VSH) analysis technique developed at the University of Michigan that permits the incorporation of the TIGCM outputs and data into the model. The VSH model will be provided for use by the Air Force in an operational setting and will be a more accurate version of existing models of the neutral upper atmosphere.

During the reporting period, the effort at the University of Michigan has focused on the further development and improvement of the VSH model. The MSIS empirical model has been incorporated into the VSH, extending the range of the model above the upper limit of the TIGCM to 1500 km. A scheme has been developed by which the model interpolates between values in the spectral coefficient library to user-specified geophysical conditions. Additionally, several changes in VSH variables and outputs have been made. Work on extending the TIGCM run set for Phase 1 Model delivery has continued. Eighteen coefficient files are presently used to run the existing VSH model, incorporating changes in season, changes in solar cycle and changes in geomagnetic activity. Additionally, several changes in VSH variables and outputs have been made.

Plans for the upcoming reporting period include continued development of the VSH approach, leading to delivery of the Phase 1 Model at the end of FY 1990. Additional key validation and model improvement efforts will be carried out at NCAR. Further TIGCM runs will be made and continuing model validation tests on these runs will be carried out. An improved treatment for the description of the output fields in the vertical dimension will be designed and implemented. Work on data ingestion techniques will continue. An improved theoretical model for neutral exospheric hydrogen will be chosen and initial efforts undertaken to incorporate it into the VSH. Lastly, an effort to coordinate the activities of the neutral and ionospheric modeling groups will continue during the upcoming period.

4.1 Progress during the current reporting period.

Appendix 4.1 reviews project milestones through the 5-year contract and summarizes the current status of the project. In spite of a late start for the first fiscal year of the contract in March, 1989, progress in model development is on schedule. Tasks 1 through 3 have been completed and the science team is currently continuing work on tasks 4 through 7 to achieve an on time delivery of the Phase 1 Model at the end of the second fiscal year.

The MSIS empirical model has been incorporated within the VSH, extending the nominal range of the model to 1500 km. For each of the TIGCM runs used as the base set for the VSH, the mid-latitude average mass density is compared to the corresponding average from MSIS. Their relative magnitudes define a normalization factor that is applied as an output field modifier for mass density at the last step in the density calculation. As part of the MSIS model implementation, hydrogen density has been added as a 13th output variable. At any altitude, hydrogen densities are obtained from the MSIS model. Above the upper altitude limit of the TIGCM, MSIS is called to specify all constituent densities.

Work has progressed on the design of the coefficient file library and its utilization in the VSH model. Rather than specifying a TIGCM run, the user specifies F10.7, Julian day, and Kp values. The VSH model then uses these inputs to determine appropriate spectral coefficients through linear combination of those determined from individual TIGCM runs (in the coefficient file library). Kp is converted to hemispheric power for purposes of finding the linear combination weights over geomagnetic activity. The weights for the day of year interpolation are found via a trigonometric scheme.

Additionally, several other changes have been made to the VSH. Meridional winds are now specified as positive northwards, rather than positive southwards. Colatitude has been replaced by latitude. Finally, mass density has been added as a 14th output variable. We are nearing completion of a technical manual for the VSH model. A second preliminary version of the VSH, updated with changes reported in the last quarterly report, was delivered to GL for further evaluation.

Presently 18 TIGCM Phase 1 runs have been completed for solar minimum and maximum conditions, three levels of geomagnetic activity, and solstices and equinox. All of the corresponding VSH spectral coefficient files have been generated. New coefficient files are being planned at present, so that a more accurate vertical representation of the state variables can be obtained, and so that data can be better integrated with the model. Further work is being undertaken to identify new TIGCM runs needed.

4.2 Plans for the next reporting period.

Plans for the next quarter of effort relate to the work statement given in Appendix 4.1. Specifically, work on tasks 4-7 will continue. Major action items for the next quarter include continued refinement of both the library scheme for Phase 1 Model delivery and the VSH algorithm, specifically the vertical and storm time representations to be utilized. Development of field and coefficient modifiers and data ingestion techniques will continue. The TIGCM sensitivity study will also continue, as will Phase 1 TIGCM runs for model delivery at the end of FY 1990. We will continue to develop further coordination of efforts with the ionospheric modelling group.

<u>Appendix 4.1</u>

Model Development Progress

● - Milestone Completed ◗ - Work in Progress ○ - Work not yet begun

Task	Subtask	Resp. Org.	FY89 M	FY89 AMJ	FY89 JAS	FY90 OND	FY90 JFM	FY90 AMJ	FY90 JAS	FY91 OND	FY91 JFM	FY91 AMJ	FY91 JAS	FY92 OND	FY92 JFM	FY92 AMJ	FY92 JAS	FY93 OND	FY93 JFM	FY93 AMJ	FY93 JAS	FY94 OND
1	Program Definition	Mich/NCAR	(late start) ●																			
2	TIGCM Verification				●																	
3	TIGCM Frozen	NCAR			●																	
4	VSH Technique Defn	Mich			◗																	
	Library Approach	Mich			◗																	
	TIGCM Input Strategy	NCAR/Mich			◗																	
5	Sensitivity	NCAR/Mich					◗															
	Defn. of # of runs	NCAR/Mich					◗															
6	TIGCM Phase 1 runs	NCAR							◗													
7	TIGCM/Exp. Merger	Mich							◗													
	DE data, SETA data	Mich							◗													
	Delivery Mark 1 NTM	Mich/NCAR							○													
8	TIGCM Phase 2 runs	NCAR/Mich									○											
	Verification above 140 km	NCAR/Mich										○										
9	Delivery Mark 2 NTM	Mich/NCAR											○									
	Verification of NTM	Mich/NCAR											○									
10	Delivery Mark 3 NTM	Mich/NCAR															○					
	Verification of NTM	Mich/NCAR															○					
11	Feasibility of operational TIGCM	Mich/NCAR															○					
12	Deliver operational TIGCM	Mich/NCAR																			○	
13	Final Validation and Final Model Improvements	Mich/NCAR																				○
	QUARTERLIES		✓	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○